Changes in water demands under adaptation actions to climate change in an irrigation district

Waldo Ojeda-Bustamante, Ronald E. Ontiveros-Capurata, Jorge Flores-Velázquez and Mauro Iñiguez-Covarrubias

ABSTRACT

Climate change will affect the water balance of irrigated agriculture. Therefore, farmers and irrigation managers should consider adapting to new scenarios. Changes in water demands in a Mexican irrigation district were studied using an irrigation-scheduling model. The impact on water demands of two potential adaptation actions, adjusting planting season and using longer-season varieties (LV), was estimated and compared with a baseline scenario. Two cropping plans (wet and dry) for the last 15 water years were considered. Cumulative and daily irrigation demands were estimated for each agricultural season and each adaptation action. The reference period (1961–1990) and three future climate projections (2011–2040, 2041–2070, 2071–2098) under A1B scenario were used. Results indicated that without adaptation water demands will decrease as temperatures increase and season lengths will shorten. However, as farmers respond with adaptation actions to maintain actual yields, water demand can be higher than non-adaptation action. The impacts of climate change on water demands depend on the adopted adaptation actions and have a greater effect on peak and cumulative demands. The water demands increased by 2.4% when LV were used and 16.3% when this is combined with adjusting planting season. Thus, adaptation actions should be chosen carefully to minimize future agricultural risk.

Key words | adaptation strategies, climate change, crop water requirement, irrigation schemes, Mexico, regional climate models

LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>D</td>
<td>Growing degree days</td>
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<td>d</td>
<td>Days</td>
</tr>
<tr>
<td>AP + V</td>
<td>Adjusting sowing/planting season and longer-season varieties adaptation action</td>
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<tr>
<td>APS</td>
<td>Adjusting sowing/planting season adaptation action</td>
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<td>B1, B2, A1T, A1B, A1F1, and A2</td>
<td>Greenhouse-effect emission scenarios</td>
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<tr>
<td>CGCM</td>
<td>Coupled General Circulation Model</td>
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<tr>
<td>CO2</td>
<td>Carbon dioxide</td>
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<tr>
<td>CWR</td>
<td>Crop water requirements</td>
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<tr>
<td>ET</td>
<td>Evapotranspiration</td>
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<tr>
<td>ET1C</td>
<td>One-crop evapotranspiration</td>
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<tr>
<td>ETa</td>
<td>Reference evapotranspiration</td>
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<td>ETp</td>
<td>Potential crop evapotranspiration</td>
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<tr>
<td>ETs</td>
<td>One-season evapotranspiration</td>
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<tr>
<td>ETzr</td>
<td>Integration of irrigation-zone evapotranspiration for a water year</td>
</tr>
<tr>
<td>fi,j</td>
<td>Weighting factor per cropped area for each sowing/planting date ‘j’ and day ‘i’</td>
</tr>
<tr>
<td>fc,i,k</td>
<td>Weighting factor per crop ‘k’ and day ‘i’</td>
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<tr>
<td>dam³ d⁻¹</td>
<td>Cubic decameters per day</td>
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INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) has indicated that because of anthropogenic emissions of greenhouse gases (GHGs), the global temperature will continue increasing during this century (IPCC 2014). The projected climate anomalies in Mexico at the end of the century indicates an increase in temperature of 5°C and a decrease in precipitation of 100 mm for the most extreme scenario in some regions (Montero-Martínez et al. 2013). Climate change might profoundly affect the water balance and, more specifically, water demand for irrigated agriculture as reported in different regions worldwide (Yano et al. 2007; Moratiel et al. 2010; Sun et al. 2012; Chaturvedi et al. 2015). However, estimation of water demands under new climate scenarios is complex because it depends not only on changes in evapotranspiration (ET) and precipitation but also on crop pattern, plant phenology, and adaptation responses from farmers (Riediger et al. 2014; Woznicki et al. 2015).

Earlier studies to evaluate the potential impacts of climate change on crop water and irrigation requirements were based on conventional ET equations and/or crop simulation models (Howell 2009). Since then, several studies have been conducted using global gridded crop models with projected climate scenarios (Konzmann et al. 2013), and usually assuming unchanged crop management (business-as-usual) and same duration of phenological stages for present and future estimations (Rodríguez-Díaz et al. 2011; Elliott et al. 2017). Daccache & Lamaddalena (2013) reported in southern Italy that peak and cumulative demand is likely to increase since future climate change projections indicate warmer and drier seasons. However, Ojeda-Bustamante et al. (2011) analyzed the expected impact of climate change on water demands without adaptation, under arid irrigated agriculture in Mexico, and concluded that water demand for annual crops will reduce between 6 and 13%, but it will increase by 7% for perennial crops by the end of the century.

As a response to new climate patterns, several adaptation actions have been suggested, such as changes in cropping pattern, sowing/planting and cultivation timing, and introduction of new crop cultivars (Olesen et al. 2011). Rolim et al. (2016) reported that seasonal irrigation requirements and flow rate increased by 15–70% and 5–24%, respectively, when new crop varieties were used as an adaptation strategy. Under
Mexico’s irrigated conditions, Ojeda-Bustamante et al. (2011) suggested the use of longer-duration cultivars and shortening the sowing period as adaptation actions for preventing reduction of actual yields. Most of the relevant studies related to potential adaptation practices have focused on crop productivity impacts. Moreover, crop water requirements (CWRs) have not been analyzed at a large scale considering changes in crop phenology and season length (Ludwig & Asseng 2010) and needs to be validated locally (Goyal 2004).

Mexico has a long irrigation tradition; for irrigated infrastructure area it ranks seventh in the world with an area of 6.5 MHa (FAO 2015). Irrigated agricultural land comprises 6.4 million ha, and generates approximately 56% of total agricultural value and up to 30% of agricultural exports (National Water Commission 2015a). Several irrigated regions in Mexico are already under high water availability pressure due to recurrent droughts and competition with other water uses. Therefore, Mexico’s agriculture will need to adapt, as the climate will be hotter and drier under intensification of climate change.

The effects on CWRs due to increasing greenhouse gas concentrations and climate change remain uncertain and adaptation plays an important role for water and food security but also for sustainable development in the future (Lengoasa 2016). Hence, the purpose of this paper is to study the effect of adaptation actions on CWRs considering the ‘Río Fuerte’ irrigation district (Sinaloa, Mexico) as a case study. The approach is to estimate CWR using a water balance-based system for baseline (1961–1990) and climate projections in early (2014–2040), mid (2041–2070), and late (2071–2098) periods, assuming changes in growing-season length (GSL) using the growing degree day concept. The assessment of impact and adaptation strategies because of climate change intensification is very important for Mexico’s food security and economy, since the studied region is very vulnerable to climate change (Ojeda-Bustamante et al. 2011) and it is one of the main grain suppliers, mainly corn, from irrigated agriculture.

**METHODS**

**Case study: irrigation district 075**

Irrigation District 075 ‘Río Fuerte’ (ID-075) is organized in 13 Water User Associations (WUAs) and is supplied by two reservoirs using two major open channels. Agriculture accounts for 93% of all water consumption, compared to 7% for other uses (domestic and industry). The global district efficiency was estimated at about 40% from reservoir to farm due to unlined open-channel networks and surface-based irrigation (National Water Commission 2015b). The methodology was applied to the ‘Santa Rosa’ Water User Association (SR-WUA), which is the largest WUA at ID-075, located in the northern state of Sinaloa, Mexico; 25.4°–26.1° N and 108.4°–109.4° W, with an average altitude of 20 m.a.s.l. The ID-075 has a farm database with detailed irrigation service information for the last 18 agricultural years, which has been generated with the continuous use of the real-time forecasting irrigation system (SPRITER) (Ojeda-Bustamante et al. 2007). This database was used to obtain the crop plan for a typical water year that in Mexico starts on October 1 (Julian day 274) and ends on September 30 of the following year.

The climate in the studied region is semiarid, with two very contrasting agricultural seasons: fall–winter (FW) that is the main agricultural season with mild temperatures, and spring–summer (SS) that is a hot season with high temperatures (Table 1). Precipitation contributions to irrigation requirements are minimal since it is concentrated from July to September when crops are not present. Therefore, irrigation is required for most of the year.

This arid irrigation district faces recurrent droughts, which induces drastic changes in cropping area; as a result, irrigation managers restrict double crops and high water demand crops in dry years reducing or canceling the SS season and concentrating crops in the FW season. Therefore, this study considers two contrasting water years: wet and dry year with 42,023 ha and 31,121 ha, respectively, for the last 15 water years. The dry year area corresponds to the actual SR-WUA command area, which is cropped

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Annual</th>
<th>FW</th>
<th>SS</th>
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<tbody>
<tr>
<td>Max temperature (°C)</td>
<td>31.3</td>
<td>26.8</td>
<td>34.3</td>
</tr>
<tr>
<td>Min temperature (°C)</td>
<td>16.6</td>
<td>12.4</td>
<td>20.3</td>
</tr>
<tr>
<td>Cumulative precipitation (mm)</td>
<td>268.9</td>
<td>219.6</td>
<td>49.3</td>
</tr>
<tr>
<td>Mean daily reference evapotranspiration (mm d⁻¹)</td>
<td>4.2</td>
<td>2.3</td>
<td>6.0</td>
</tr>
</tbody>
</table>
once, having only FW and Perennial (PER) seasons. The annual seasons are almost monocropping in the last two decades with cropping patterns according to Table 2. The main crops in the FW season are *Zea mays* (corn), *Phaseolus vulgaris* (common beans), *Solanum tuberosum* (potato), *Lycopersicum sculentum* (tomato), and other horticultural crops. During the SS season the main crops are *Sorghum bicolor* (sorghum), corn, and other horticultural crops. *Saccharum officinarum* L. (sugarcane) is the main perennial crop, other perennial crops are fodders (mainly *Medicago sativa*, alfalfa), and orchard crops (mainly *Mangifera indica*, mango). Annual crop area (FW + SS) was 88.9% for the wet year and 85.0% for the dry year, respectively.

In the SR-WUA there is a broad sowing/planting period for crops during a typical water year. The FW sowing/planting takes place during the cold period from Julian day 280 to the 15th of the following year (beginning of October to mid-January) (Figure 1). With the exception of tomato, which has a broad sowing period, the FW harvesting period is concentrated from Julian day 1 to day 140 (from the beginning of January to mid-May). Cropping planting frequencies were estimated from historical data assuming an interval of 10 days. Therefore, for simulation purposes, all planting in each decadal period is concentrated in the middle of each period. For example, 13 decadal sowing periods resulted for corn, from late September to late January. In terms of cropped area, FW is the main agricultural season, as shown in Figure 1. PER is very stable and SS is highly dependent on water availability. Therefore, when the SS cropped area is reduced, it indicates that water availability is very limited.

### Table 2

<table>
<thead>
<tr>
<th></th>
<th>FW 26,452.8 (26,452.8) ha</th>
<th>SS 10,892.3 (0) ha</th>
<th>PER 4,656.8 (4,656.8) ha</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common beans</strong></td>
<td>13 (25)</td>
<td>Corn 24 (0)</td>
<td>Fodders (alfalfa) 6 (6)</td>
</tr>
<tr>
<td><strong>Corn</strong></td>
<td>62 (51)</td>
<td>Sorghum 71 (0)</td>
<td>Sugarcane 92</td>
</tr>
<tr>
<td><strong>Potato</strong></td>
<td>19 (19)</td>
<td>Others 5 (0)</td>
<td>Orchards (mango) 2 (2)</td>
</tr>
<tr>
<td><strong>Tomato</strong></td>
<td>4 (3)</td>
<td>Others 2 (2)</td>
<td></td>
</tr>
</tbody>
</table>

Note: Wet year area = FW + SS + PER; dry year area = FW + PER.

### Climate change projections and datasets

Currently, the climate change is evaluated by using quantitative climate data generated from Coupled General Circulation Models (CGCMs) under different socioeconomic and technological development assumptions (Izaurralde et al. 2003; IPCC 2013). However, due to differences in their conceptualization and parameterization of physics and dynamics of atmosphere, these models present an uncertainty in the projected evolution of climate. To bound uncertainty, the IPCC in its Fourth Assessment Report considers 23 CGCMs, which include six different
scenarios for greenhouse effect cases (GHG) emissions known as Special Report on Emissions Scenarios (SRES): B1, B2, A1T, A1B, A1F1, and A2 (IPCC 2000). In this study, the medium moderate (A1B) emission scenario was used; it is the most frequently used in climate change studies. A1B considers that society will use all renewable and limited energy sources in a balanced manner, including fossil fuels (IPCC 2000).

Adequate downscaling of CGCM climatic projections is necessary to study most impacts of climate change at local and regional scales (Yano et al. 2007). Therefore, monthly regional climate projections for the 2011–2098 period were used, with a regular grid of 0.5° × 0.5° (~50 × 50 km) derived by statistical downscaling from CGCM model data as was reported for Mexico by Montero-Martínez et al. (2013). Since there are considerable variations among climate models and there is not a unique CGCM that replicates past Mexican climatology, a probabilistic distribution of future climate change was used to combine different CGCMs in a single climate ensemble of CGCMs, which has been recognized as preferred instead of using an individual CGCM (Winkler et al. 2011). The projected precipitation and air temperature (maximum and minimum) data were obtained through weighted averages of the best CGCM projections for Mexico, available at the IPCC data distribution center (www.ipcc.data.org), using the reliability ensemble averaging method proposed by Giorgi & Mearns (2003). This method allows generation of a ‘mean’ climate change projection based on probabilistic ensemble projections weighted of 23 CGCMs considering combined individual model bias and model convergence to ensemble mean.

Climatic data series were divided into four time periods: P0, P1, P2, and P3. The first, P0, is related to the recent past and corresponds to the average of climate variables for the base period (1961–1990). The P1, P2, and P3 scenarios define the average of monthly values for the periods 2011–2040, 2041–2070, and 2071–2098, respectively. Average monthly values were generated for the climate variables of temperature and precipitation for each time period for the A1B scenario. The climate data for the 1961–1990 period were obtained from ‘Los Mochis’ meteorological station (25.82° N, 109.0° W, and 14 m.a.s.l.), which is considered representative of the study area, as reported by Ojeda-Bustamante et al. (2011).

Water demand estimation

The estimation of CWRs during a water year for large irrigation zones was estimated with a developed computer program (Reqgo-ZR), based on soil water balance simulation model equivalent to CropWat (Clarke et al. 1998). The CWR estimation had the following assumptions:

- The CWR was calculated using FAO methodology (Allen et al. 1998).
- Irrigation scheduling parameters (crop coefficient and rooting depth) were estimated using a validated model as function of cumulative growing degree days according to Ojeda-Bustamante et al. (2006).
- Cropping planting frequencies were calculated from field data, assuming an interval of 10 days for each crop sowing/planting season.
- Three agricultural seasons were considered: PER, FW, and SS. However, FW is the main agricultural season.
- No future changes in cropping patterns were assumed.
- CWRs are proportional to cultivated area per each crop, season, and water year.

With the above assumptions, the daily evapotranspiration calculation process considered the following five steps (Íñiguez-Covarrubias et al. 2011):

1. Reference evapotranspiration calculation ($ET_o$): The $ET_o$ was calculated with the Penman–Monteith equation as recommended by FAO (Allen et al. 1998).
2. Potential crop evapotranspiration ($ET_c$) per sowing/planting date calculation for each crop: CWRs were calculated according to the FAO methodology (Allen et al. 1998) in the form of $ET_c = K_c ET_o$ where $K_c$ is the crop coefficient expressed in function of the cumulative growing degree days (°D) based on the equations proposed by Ojeda-Bustamante et al. (2006). The use of Reqgo-ZR program eased the calculation of the crop length season since the degree days’ concept is a good predictor of plant growth. $K_c$ parameters have been calibrated locally for most crops grown in the study area, as reported by Ojeda-Bustamante et al. (2006) for corn. An $ET_c$ curve was generated for each sowing/planting date for a given crop, as shown in Figure 2, for four
sowing/plating dates (October 15, November 15, December 15, and January 15).

3. Integration of actual crop evapotranspiration curve ($ET_{1C}$): A unique curve per crop is obtained by weighting, as a function of sowing/planting area per sowing/planting date at each day $i$ (Figure 2). The estimation of $ET_{1C}$ for day $i$ is estimated with contributions from all sowing/planting $ET_r$ curves:

$$ET_{1C-i} = \sum_{j=1}^{N_{pd}} f_{ij}ET_{r-j-i} = \sum_{j=1}^{N_{pd}} f_{ij}K_{c-i,j}ET_{0-i}$$

where $N_{pd}$ is the number of sowing/planting dates considered for each crop. For each day $i$, $ET_r$ curves were weighted considering all sowing/planting dates per each crop. The index $i$ spans from first sowing/planting date to last harvest date of all $N_{pd}$ curves. $K_{c-i,j}$ is the daily variation of crop coefficient for each sowing/planting date $j$, $ET_{r-i}$ is the $ET$ per sowing/planting date $j$ for each day $i$, and $ET_{0-i}$ is the reference evapotranspiration for day $i$, $f_{ij}$ is the weighting factor per cropped area for each sowing/planting date $ET$ curve $j$ and day $i$ estimated by:

$$f_{ij} = \frac{S_{ij}}{S_{t-c}}$$

where $S_{ij}$ is the cropped area for sowing/planting date curve $j$ for day $i$. $S_{t-c}$ is the total cropped area for the crop ‘c’ in the season. As an example, Figure 2 shows a unique actual crop evapotranspiration curve ($ET_{1C}$) for corn, considering four sowing/planting date curves ($N_{pd} = 4$).

4. Integration of one-season evapotranspiration ($ET_s$): $ET$ for all crops in a season is integrated in a single $ET$ curve. The seasonal $ET$ was calculated as follows:

$$ET_s = \sum_{l=FP}^{LH} \sum_{k=1}^{N_c} f_{c-i,k}ET_{1C-i,k}$$

where $N_c$ is the number of crops per season, $f_{c-i,k}$ is the weighting factor per crop $k$ and day $i$ expressed as follows:

$$f_{c-i,k} = \frac{S_{i,k}}{S_{t-s}}$$

$S_{i,k}$ is the cropped area for day $i$ and crop $k$. $S_{t-s}$ is the total cropped area in the season $s$ considered. Three agricultural seasons were considered: PER, FW, and SS.

5. Integration of irrigation zone evapotranspiration for water year ($ET_{zr}$): An integrated $ET$ for the water year is estimated. The $ET_{zr}$ per day $i$ is the sum of weighted contribution of all three seasons ($ET_s$) considered:

$$ET_{zr-i} = \sum_{l=1}^{N_s} f_{s-i,l}ET_{s-i,l} = f_{FW-i}ET_{FW-i} + f_{PER-i}ET_{PER-i} + f_{SS-i}ET_{SS-i}$$

The estimation of weighted factor ($f_{s-i,l}$) for season $l$ and day $i$ is estimated as follows:

$$f_{s-i,l} = \frac{S_{i,l}}{S_{t-y}}$$

where $S_{i,l}$ is the cropped area for season $l$ and day $i$, $S_{t-y}$ is total irrigated area (command area) in the water year. The total physical irrigated area is the cropped area of FW plus PER, since SS crops are double crops.

With the crops’ surface percentages established per agricultural season, the crops’ water demand curves were
obtained for the three agricultural seasons in a water year for the SR-WUA during the four periods studied considering possible adaptation actions. This study does not consider the possible beneficial effect of the increase in carbon dioxide on the reduction of crop transpiration, as reported by Lawlor (2005), because of limited information about this effect under drought and thermal stress conditions in these crops.

**Cropping adaptations**

Climate change will impose new challenges on irrigation managers as water demand will change spatially and temporally, and may increase, as climate change intensifies and farmers adopt several actions to reduce its impact on crops. Since changes in crops are explained as a function of various driving factors (biophysical, demographic, socioeconomic, and technological), it is difficult to make predictions on possible cropping patterns in the future (Pérez-Urrestarazu et al. 2010). However, it is possible to establish locally the most likely adaptation actions. Ojeda-Bustamante et al. (2011) reported two adaptations of farmers’ responses to maintain actual crop productivity in a Mexican irrigation district: use of longer-duration varieties and reduction of sowing/planting dates towards the colder season as warming intensifies in the future. In this way, four adaptation actions are analyzed in terms of expected cropping management changes:

1. Without adaptation (WA). This reference case, called ‘Dumb farmer’ scenario (Rosenberg 1992), assumes that no attempts to adjust or adapt farms to climate change will be made in the future. Farmers will act as if nothing had changed and the same planting date and varieties would be used.
2. Adjusting sowing/planting season (APS). As it gets warmer, it is assumed that farmers will move the sowing/planting period to cold periods to create a longer growing season to maintain actual yields.
3. Using longer-season varieties (LV). As it gets warmer, it is assumed that farmers will use LV that will be tolerant to thermal and drought stress, and which can endure higher temperatures than those present today.
4. A mixed approach (AP + V). Both adaptation alternatives are implanted: adjusting planting season (APS) and new LV.

CWRs were estimated for the four adaptation cases considering three future periods, P₁, P₂, and P₃. These simulations were generated for the wet year, which correspond to the year with maximum water demands.

**RESULTS AND DISCUSSION**

**Actual scenario (Pₒ)**

Changes in the water requirements (ETᵢ) and GSL of corn with planting dates are shown in Figure 3. Although there is a broad planting period for FW corn from Julian 250 to 31 (from mid-September to the end of January), the main planting period is from Julian day 274 to 350. In this period the differences reached 15 days in season length and 100 mm in CWRs. Corn’s most productive period in the ID-075 is related to planting date that produces longer FW growing season concentrated from Julian 293 (October 20) to 324 (November 20), outside this period, the length of season is shorter. Thus, CWRs depend on the planting date but a shorter length of season does not necessary indicate lower CWRs, as shown in Figure 3.

The demand volume peak in FW is a little higher than for SS in a wet year (Figure 4), while in dry years, no SS is cropped due to water availability and the FW season defines demand volume in a water year, as shown in Figure 4(b). Dry cases are more common in the studied region due to water availability reduction. This kind of reactive adaptation, canceling...
or reducing double crops in SS, has been historically applied in
the study region due to climate variability resulting in contrast-
ing water demands between wet and dry years. Figure 4 shows
an inter-annual variation up to 26% on daily water volumes
demanded by the crops when comparing wet versus dry years.

Climate change projections

The average trend-line projected by CGCM models indicates
an annual increase in average temperature of 0.05 °C per
year in the 2010–2098 period for ID-075, considering the
A1B emissions scenario. The average monthly daily tem-
perature, compared to P0, will increase on average 1.0, 2.2,
and 3.0 °C during periods P1, P2, and P3, respectively. The
annual variation of precipitation will decrease less than
30% by the end of the century as compared to the average
P0 value. Annual rain will decrease on average 62, 70, and
110 mm during the P1, P2, and P3 periods, respectively.

An annual accumulated ET0 value of 1,554 mm was esti-
mated for the base period P0. When introducing CGCM
projections into the meteorological variables for the A1B
emissions scenario, an increase in annual ET0 was esti-
mated, as compared to P0, of 3, 6, and 10% in the P1, P2,
and P3 periods, respectively.

Impact of climate change on corn water requirements

The effect of A1B warming scenario was simulated on FW
corn water requirements for the same sowing/planting day
(November 15) considering the mid-term period P2. Without
adaptation, CWR (peak and cumulative) will be lower in the
future (WA-P2 curve). It will shift peak demand with respect
to actual (WA-P0) due to a shortened growing season
(Figure 5). This decrease in ET was reported by Yano et al.
(2007) and can be attributed to a reduction in growing
days and leaf area in response to temperature and transpira-
tion rise due to stomatal closure regardless of increased
 evaporative demand. To counteract this effect, it will be
necessary in the future to use varieties with greater growing
degree days requirements (longer season) to maintain yield
and equivalent length season. However, maintaining a simi-
lar length of growing season at mid-century will generate a
higher peak and cumulative CWR (curve LV-P2). As reference, Figure 5 shows the actual curve for the baseline period (WA-P0). Peak $E_{T_r}$ values were 5.5, 5.0, and 5.7 mm $d^{-1}$; and cumulative $E_{T_r}$ were 512, 442, and 546 mm for WA-P0, WA-P2, and LV-P2 curves, respectively.

**Impact of climate change on daily water demands**

Figure 6 integrates daily demand-flow curves considering several adaptations’ actions (WA, APS, AP + V, LV) for the wet water year. Simulation results indicated that for P2 the use of LV will have more pronounced effects in daily flow than for the APS case. Without adaptation, the increase in temperature will shorten the growing season of all annual crops generating a peak shift toward cold months; these trends are similar to those reported by Ojeda-Bustamante et al. (2011). Combined adoptions of adaptation actions (AP + V) can generate similar peak and higher cumulative CWRs than actual values (WA-P0), as shown in Figure 6. In consequence, irrigation systems must be analyzed based on future water demand during the water year to supply peak demands, temporally and spatially.

**Impact of climate change on cumulative CWRs**

Table 3 shows cumulative CWRs ($E_{T_{sr}}$) considering four adaptation actions during four periods assuming that future crop patterns remain similar to the baseline period. Without adaptation, crop water demands will decrease about 10.9% at the end of the century due to increase in temperature, and will be more pronounced for WA than for the APS case. An increase in temperature will cause a reduction of GSL for annual crops. This effect will have a major impact on the increase of reference evapotranspiration and will also implicate reduced yields due to a reduction of CWR. Higher values can be obtained if PER and SS crops cover more area than actual values. Using LV and AP + V actions, crop water demand will have higher values than for WA and APS actions and will be more pronounced in the late future periods. Adopting a LV strategy, the water demand was 3.9% lower than AP + V for the P3 period and it can be a viable adaptation action to recover actual crops’ season length. AP + V action produced the highest increase in cumulative CWRs, 16.3% more than the P0 period.

The CWRs at irrigation scheme level ($E_{T_{sr}}$) will decrease in the future climate when no adaptations are considered, as found by Moratiel et al. (2010) and Ojeda-Bustamante et al. (2011). The use of LV as an adaptation strategy will recover actual crop duration but it might increase crop water demands to higher values than current ones, as also reported by Islam et al. (2012).

**Impact of climate change on peak CWRs**

The $E_{T_{sr}}$ peak in P0 occurs in warm months, mainly during April (105–115 Julian days). However, as the climate change intensifies, these peak values will shift to colder months for cases WA and APS (P2 in Figure 6). This nullifies the effect of increasing peak water demand due to an increase in temperature since this shortening of season shift cancels out the increase in $E_{T_{sr}}$.

In a similar way to cumulative CWRs, Table 4 indicates estimated peak CWRs considering four adaptation actions during three future periods. Peak CWR for WA and LV actions can be reduced by 33% and 6.7%, respectively, at the end of the century (P3), but for APS and AP + V cases, peak CWR increased 4.4% and 13.3%, respectively, in the same period. This is due to an effect of adjusting sowing/planting season and cultivars’ season length. The simulations indicated lower peak water demand, with respect to reference period P0, for all cases in the period P1 and
P2 followed by an increase during periods P2 and P3. WA was the only case where the peak water demand did not increase and continued to decline towards the end of the century. When using combined adaptation actions (AP + V), peak CWRs had an increase of 13.3%. This value can be much higher if global efficiencies are considered to estimate volume at source level for an irrigation scheme. These results indicate that it will be important for irrigation managers to consider climate change assessment in large irrigation schemes and the future implications on canal capacity and irrigation service at peak water demand periods.

The above results are valid assuming a cropping pattern where most crops, mainly corn, are concentrated in the FW season, as is the case in most Mexican irrigation districts.

**Study limitations**

It should be mentioned that this analysis assumed the A1B emission scenario and did not consider the combined effects of rising temperature and CO2 that may produce antagonistic outcomes on water demands and crop yield, but there is insufficient information about these effects (Rolim et al. 2016). It was also assumed that there would be neither phytosanitary nor weeds and nutritional problems. Agromonic practices, technological development, and cropping pattern were also assumed similar in the future. Therefore, further research is required to clarify the effect of other combined potential adaptations and their possible interactions at irrigation scheme level. It is also necessary to analyze in detail other viable adaptation actions not studied in this paper, such as crop reconversion and the use of deficit irrigation, water conservation and harvesting techniques in irrigated agriculture. This study is based on the SRES scenarios because several studies have analyzed future climate impacts using these scenarios as reported by Ojeda-Bustamante et al. (2011). However, it is important to use new projections based on the Representative Concentrations Pathways released by IPCC (2013) in Assessment Report 5 according to expected radiative forcing level. Important differences can be found if other cropping patterns are used, for example, if SS and PER seasons have similar or higher cropped areas than the FW season.

**CONCLUSIONS**

Assessment of potential impacts of climate change on irrigated agriculture must analyze not only changes on climatological variables but also repercussions on irrigation response variables, such as crop water demands (peak and cumulative). It should also consider potential farmers’ actions, a new information available, such as changes in agricultural management and new projections from CGCMs.

As farmers adapt to climate change to maintain actual and crop yields, water demands can be higher, as shown in the case study. Longer-season varieties and combined with sowing/planting season adjustment might have higher
cumulative crop water demands compared to the reference period. Adopting LV and combined with adjusting planting date strategies, the water demands were 12.4% and 16.3%, respectively, higher than the reference period at the end of century.

This analysis indicated that peak CWR will change at the end of the century as warming intensifies in response to season length shortening. Results indicate that without adaptation actions or using LV, the peak CWR will be reduced by 33% and 6.7%, respectively. It may increase up to 4.4% when using adjusting sowing/planting dates, and if this is combined with LV, it will be higher than the reference period by 13.3%.

Therefore, to maintain actual performance, irrigation schemes will have to adjust for future water demand when irrigation managers and farmers simultaneously implement adaptation actions. Finally, this study indicated that inter-annual variation of volumes available for irrigation due to climate variability must be considered. This analysis is very useful to estimate the effect of adaptation actions on CWRs which can also provide information about changes in canal capacity and in the irrigation service.

REFERENCES


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