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Investigating Tradeoffs between Agricultural Development and Environmental Flows under Climate Change in the Stung Chinit Watershed, Cambodia

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Abstract: The interlinkages between water for irrigation and for fish habitat are complex. This is particularly true in the Stung Chinit, a tributary to one of the most robust fisheries in the world, where livelihoods rely heavily on rice production and fishing and there is pressure to increase rice production with increased irrigation. This study assesses the tradeoffs between various management options and irrigation strategies in the Stung Chinit watershed under multiple projections of climate change. Due to the relative demands for instream flows and rice, if dry season rice is widely promoted, flows will be severely impacted. However, implementing a flow requirement protects these flows, while only causing minor shortages to rice when planted once or twice per year. These shortages may be alleviated with improved cooperation, management and shifting rice irrigation practices. While climate change will lead to warming temperatures and potentially higher demands for irrigation, the larger threat to rice and ecosystems appears to be water management (or lack thereof). This study suggests that there is sufficient water in the system to expand the irrigated area by 10%, grow rice twice per year and protect downstream flows under climate change; however, well-coordinated management is required to achieve this.

Keywords: water management; irrigation; environmental flow; rice production; climate change; Cambodia

1. Introduction

Cambodia, one of the most vulnerable countries in Southeast Asia to climate change [1,2], will likely experience higher precipitation, increased seasonality and increasing temperatures under the changing climate [3,4]. With a monsoon-driven tropical climate, Cambodia already experiences many types of hydro-meteorological hazards including droughts, heavy storms and both flash and prolonged flooding, which may become more extreme under climate change [5]. It is not just the climatic impacts that makes Cambodia vulnerable, but people's reliance on climate-sensitive activities and the challenges faced in water management. People in Cambodia rely heavily on rice and fish for food while rice production, fishing and forestry employ 70% of the labor force [6,7]. Rice, specifically, is a major consideration in the national food security effort [8,9], ever more important in a country where 26% of the population remains malnourished [2]. Rice production already faces the challenges of floods and droughts and rice farmers have expressed concerns over their ability to adapt to climate change, reporting adverse field conditions under higher temperatures and less rainfall and subsequent reductions in yields [10,11].

While climate change poses an important risk to the country's natural resources, agricultural expansion continues to be an important economic goal and the practices and infrastructure to achieve this may in fact provide climate adaptation strategies [12,13]. Modern rice varieties with shorter rice cultivation periods can provide surplus production beyond the traditional wet season cultivation [14]. This practice of double-cropping has gradually increased in Cambodia since the introduction of short- and medium-duration rice varieties [15]. Multiple cropping can not only ensure subsistence for rice-growing households but can provide an additional source of income and can allow for flexibility in response to erratic changes in rainfall patterns [16].

Despite progress made in increasing the number of rice plantings per year, Cambodia suffers from low rice yields relative to other rice-producing countries in the region [17] due to a variety of reasons, but most notably due to poor water management related to too much or too little water [9,12]. Cambodia's climate of extremes—too much water in the wet period, and insufficient in the dry period—makes water management essential for the continued development of agriculture and adaptation to climate change [18]. While double-cropping has increased during the wet season, less than 10% of rice is grown during the dry season due to limited water availability, lack of irrigation systems and insufficient reservoir storage [14,17]. A study in the Pursat River Basin suggests that reservoir development can be one of the water management options to adapt to the expected significant declines in future water availability [11]. However, reservoir development options cannot be contemplated in isolation from the upstream activities related to land use changes [19], the increasing water infrastructure development in the Mekong watershed and impacts on flow regimes and aquatic species [20]. Recent studies suggest that adaptation options need to be evaluated at the community level, focusing on improving irrigation technologies and community-level monitoring systems [10].

Community-level irrigation infrastructure is not only required to make dry season rice production possible but can also provide added water security and reliability in a changing climate [16]. Murphy et al. indicates that infrastructure development and less water-intensive methods for rice production can contribute to the reliability of the system and the reduction of greenhouse gas emissions from rice [21]. This research emphasizes the notion that community-based environmental management can be a key intervention to counteract the "perceived inadequacies of top-down or central government management" [22]. Technical models can provide the tools to scale-up community-based actions to examine the implications of those actions at the watershed level, which can in turn contribute to the coordination between water users, but this would require multiscale water governance, another area where Cambodia faces challenges.

Recent changes in water governance have caused fragmented decision-making processes and left the system dysfunctional in places [7]. Irrigation supply relies on Farmer Water User Communities (FWUCs), which are local government entities made up of farmers with limited resources, power or capacity. These challenges limit farmers' independence and ability to respond with large-scale adaptation measures, such as growing dry season rice [23]. A number of studies have shown that increased fertilization and irrigation are important climate change adaptation actions available to farmers [24,25]. However, watershed level impacts on the hydrology need to be evaluated—in particular, impacts on the downstream parts of the watershed and the potential tradeoffs between irrigated agriculture and required flows for fish habitats [24,25]. The very irrigation practices, fertilization and multiple cropping that may make rice farming less vulnerable against climate change may have the opposite effect on fish populations. Stresses on water supply from climate change and increases in demands from rice production goals will require better management of water resources to ensure sustainability of livelihoods and ecosystems.

Cambodia is currently faced with many challenges, from extreme weather events to low rice yields, desires to increase rice production but a lack of water management to do so effectively and a population that relies on the health of agriculture and fisheries to survive. Climate change will likely exacerbate all these challenges. While many studies have been conducted to understand the potential impacts of climate change on water availability and hydrology [18,26–29], how and to what extent rice production can reliably and sustainably expand under climate change is still largely uncertain. This study aims to better understand the interconnectedness of climate change, rice production and potential impacts of both to downstream flows required for fish habitat and other ecosystem services. We provide a watershed-level analysis of climate change impacts and water management implications for people, food security and the sustainability of ecosystem services in the Stung Chinit watershed by investigating the tradeoffs between different strategies of increasing rice production and protecting environmental flows. The Stung Chinit is a watershed where community-managed water resource systems are grappling with the complexities of conflicting objectives of producing more rice and supporting fishing activities while they are developing their water governance and infrastructure under a changing climate. This is a challenge that is shared by other watersheds in the region and worldwide. We first describe the Stung Chinit watershed and the specific challenges which it faces relevant to climate change and water management, we then describe the model developed to conduct the analysis, the analysis itself and, finally, findings and discussion.

2. Study Area

The Stung Chinit, at approximately 264 km long with a watershed of approximately 8236 km^2, is located primarily in Kampong Thom Province in Cambodia (Figure 1). The river is a major tributary of the Tonle Sap Lake (Figure 1), the largest and most important lake in Cambodia both in terms of economy and water supply, supporting one of the world's most productive ecosystems [30]. Like the rest of Cambodia, rice production and fishing are essential to the lives and livelihoods of those living in the basin, but at times, these objectives may be at odds. Large-scale global changes such as hydropower development, climate change and urban migration are expected to negatively impact individuals who depend on fisheries of the Tonle Sap [31]. This watershed has been found to be particularly vulnerable to climate extremes, considering different areas in Cambodia [18].

Approximately 90% of cropland in the Stung Chinit watershed is rice, with the majority of rice cultivation occurring in the wet season [17]. While irrigation schemes exist within the basin, most of the rice is rainfed and multiple cropping is still uncommon [14]. After the development of irrigation schemes in the Stung Chinit watershed, villages downstream noted declines in fish size and populations in the dry seasons due to lower than usual flows, with water levels that limit their ability to travel by boat [18].

In the Stung Chinit watershed, there are two main reservoirs as well as multiple smaller reservoirs and ponds, which supply irrigation water to farmers' fields through a system of primary, secondary and tertiary canals. The two main reservoirs, the Stung Chinit and Taing Krasaing (Figure 1), and their primary canals, though built by the national government, are now managed by the Provincial Department of Water Resources and Meteorology (PDoWRAM), and the secondary and tertiary canals are managed by the Farmer Water User Communities (FWUCs) [23,32].

FWUCs may operate in different ways. In the Stung Chinit FWUC, which manages canals in one of the larger irrigation schemes, irrigation scheduling is done in coordination with farmers and the Chinit River Irrigation Committee, and farmers are included in all steps of the irrigation planning [32]. This method seems to be operating well, as the majority (75%) of farmers indicated that they receive sufficient water at the right time [32]. Those with access to water from the canals have seen improved livelihoods due to the development of the irrigation scheme, as they can plant rice earlier, more reliably and in the dry season [18].

Figure 1. Map of the Stung Chinit watershed, including two reservoirs, with precipitation stations and streamflow gauges used in this study. The inset map shows the watershed's location within Cambodia.

A site visit to the Taing Krasaing FWUC demonstrated that schedules are set more ad hoc, based on rain events, but timing of releases is communicated to farmers, and farmers can request additional water when needed. (As part of this study, three workshops and one site visit to the two reservoirs in the system were conducted between April and December of 2018. As it pertains to this work, the workshops served to give stakeholders an opportunity to give input and learn from the model development and analysis. Participants included members of the PDoWRAM, Provincial Department of Agriculture and Department of Environment, Commune and District government leaders and FWUC, forestry and fishery community leaders and members.) Among other FWUCs, some may develop set schedules for the release of irrigation water into canals, some may have an allocation method but may not discuss it with farmers, and others still may operate on an ad hoc basis with little planning and coordination, only operating based on daily needs [33]. Overall, cooperation and management within the basin is found to be lacking the capacity to respond to the threats which climate change poses [18].

3. Model Description

3.1. Model Formulation

To effectively evaluate the linkages between the natural hydrology of a system and effects of climate change with man-made infrastructure, planning and policy elements such as reservoirs and their operations, irrigation demands and instream flow requirements; an application of Water Evaluation and Planning System (WEAP) was developed for the Stung Chinit watershed [34]. The Stung Chinit WEAP Model is a weekly time-step model that incorporates surface water quantities, root zone processes and a representation of the reservoir and irrigation system within the watershed. The model includes the two main rivers in the watershed: the Stung Taing Krasaing and the Stung Chinit. The watershed has eight main irrigation schemes supplied by two reservoirs: the Stung Chinit and Taing Krasaing. The model has a detailed representation of these irrigation systems and a courser representation of the domestic water use in the villages. The historical model period extends between 1985 and 2017 and future scenarios were developed and run for 2019–2099. The following sections describe the input data and assumptions behind the model development for both the historical period and the future scenarios.

3.1.1. Water Evaluation and Planning

WEAP is a watershed modeling software that can be used to model the natural hydrologic system of a watershed as well as the man-made infrastructure, water-related policies and corresponding demands, including ecosystems [34]. The application of WEAP for this analysis utilizes WEAP's built-in methods for modeling rainfall-runoff and detailed crop irrigation requirements from climate, land use and detailed crop input data. The application of WEAP used in this study simulates available flows in the river and then stores this water in the reservoirs or allocates available water to domestic water demands, rice production or environmental flows downstream, based on management rules specific to each scenario investigated.

3.1.2. Catchments and Land Use

The Stung Chinit watershed is divided into 20 WEAP catchments (Figure 2, Table A1). The irrigated areas of the Stung Chinit and Stung Taing Krasaing irrigation schemes, which receive water from either of the reservoirs via canals, are represented by eight of these catchments, referred to as "irrigated catchments" and named by their group (Figure 2, Table A1). The irrigated catchments represent a relatively small portion of the total model area (<186 km^2). The remaining area, the majority of the basin (~7514 km^2), is not irrigated, only rainfed, and it is represented by the remaining twelve catchments, referred to as "non-irrigated catchments". These are numbered from upstream to downstream (Figure 2).

Land use is represented in each of the 12 non-irrigated catchments by nine land use categories that vary annually between 2002 and 2015 in the historical period, based primarily on the land use information developed by Winrock International for the Watershed Ecosystems Services Tool (WESTool), for years 2002–2015 [35]. Some land use categories from WESTool were grouped for the WEAP application (Table A2). Table A2 and Figure 3 show land use in 2002 and 2015, to demonstrate the overall land use change in the area. Due to lack of information before and after this period, land use was held constant. In the areas classified as "non-irrigated rice", fields contain a 20–30 cm berm that holds rainwater falling onto the landscape and floods if sufficient rain occurs. No additional water beyond precipitation is available to these areas. In the areas categorized as "mosaic cropland" (Figure 3), a crop with a kc = 1.1 is planted, grown without berms and not irrigated with water other than rainfall.

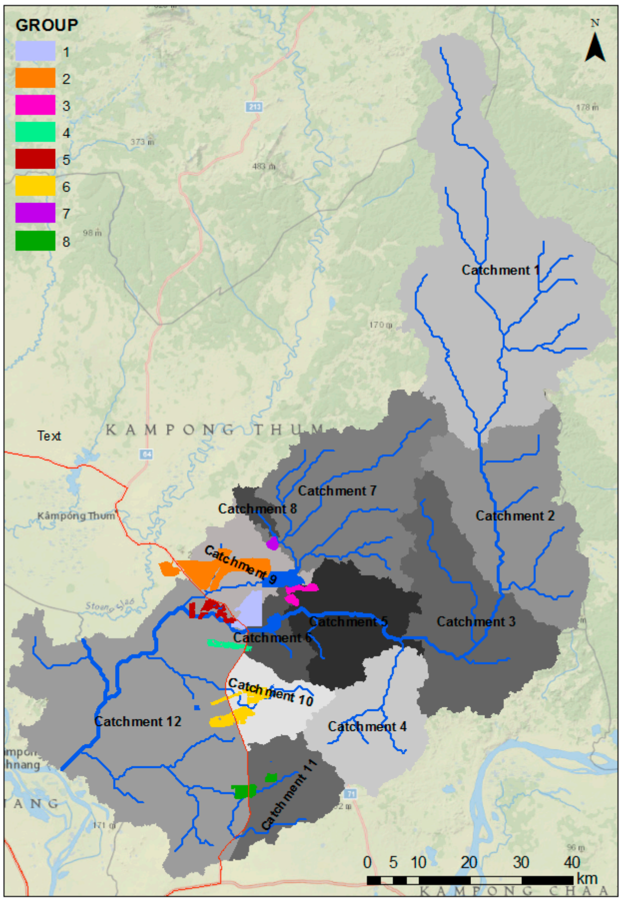

Figure 2. Map of the Stung Chinit watershed, divided into 20 WEAP catchments, with non-irrigated catchments shown in grey and irrigated catchments in color.

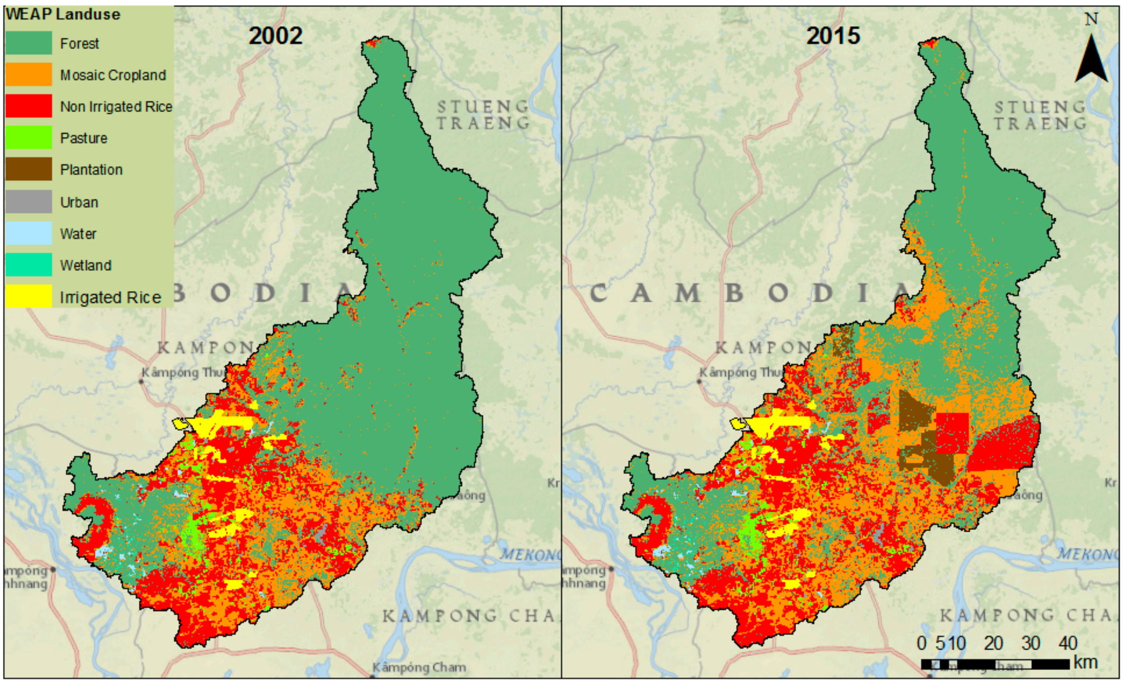

Figure 3. Land use in 2002 and 2015, colored by WEAP land use categories.

Within each of the WEAP catchments, rainfall-runoff and irrigation demand is calculated using two different methods. The non-irrigated catchments use the soil moisture method to calculate rainfall-runoff, which represents the root zone with two buckets [36]. The other method is used in the irrigated catchments where rainfall-runoff and the irrigation demand are calculated using WEAP's MABIA method [36]. The MABIA method includes detailed information on crop scheduling, irrigation practices and irrigation demand calculations based on the Food and Agriculture Organizations Drainage Paper 56 [37]. It contains a daily simulation of transpiration, evaporation, irrigation requirements, irrigation scheduling, crop growth and yields and includes modules for estimating reference evapotranspiration and soil water capacity. This method is most useful for representing cropping patterns, especially double cropping, as well as planting different crop varieties. The details of irrigated catchment areas and the underlying assumptions for the historical period are described in Table 1.

Table 1. Description of irrigated areas in the historical period as included in the WEAP model and the underlying assumptions. Basis of assumptions is further explained in the reservoir section of this paper, Section 3.1.5. Prior to 2007, there is no irrigated area within the basin; therefore, the irrigated catchments do not model any area in the historical period during this time. Starting in 2007, however, the area modeled in these catchments increases according to the areas listed below. Before, after and between years, irrigated area is held constant.

Irrigated Area by Group and Year (km^2)									
Year	**Group 1**	**Group 2**	**Group 3**	**Group 4**	**Group 5**	**Group 6**	**Group 7**	**Group 8**	**Total**
2008	9.5	0.0	0.0	2.9	5.2	11.5	0.0	0.0	29.2
2009	30.0	0.0	0.0	9.3	16.4	36.2	0.0	0.0	91.8
2017	30.0	76.6	12.1	9.3	16.4	36.2	4.5	0.0	185.1
2018	30.0	76.6	12.1	9.3	16.4	36.2	4.5	4.8	189.9

Assumption by Year	
2007	No irrigated area
2008	The Stung Chinit reservoir starts supplying irrigation water in 2008 to 29.21 km^2, approximately 30% of the total area, so 30% of each group that receives water from the Stung Chinit system (Groups 1, 4, 5 and 6) begins receiving water in this year
2009	Starting in 2009, the Stung Chinit reservoir supplies water to the entire command area (Groups 1, 4, 5 and 6).
2017	Starting in 2017, the Taing Krasaing reservoir starts supplying water to its entire command area (Groups 2, 3 and 7).
2018	The expansion of the Stung Chinit system allows for 1/3 of Group 8 to receive water starting in 2018.

Most water use is constituted by irrigation in the Stung Chinit watershed. The selected scenarios are designed to evaluate the viability of increasing rice production while considering the existing irrigation system and potential climate change impacts. To assess the impact of potential irrigation expansion on water resources availability, the irrigated area was either held constant at the 2018 values or increased by 10% for each group's rice area. The increase in area was subtracted from the bordering non-irrigated catchment to preserve the total area of the basin. These scenarios represent the development of new canals or extensions of the existing canal system.

3.1.3. Irrigated Rice Representation

It is assumed that all irrigated catchments are growing rice based on information from Nesbitt [17]. In the historical period, and in the baseline future scenario, all irrigated areas grow one medium variety of rice, Pkar Romdoul, once a year during the wet season. This is likely an underestimation of rice grown in these areas historically, because, during project workshops, some farmers indicated that they grow rice two, three or even four times per year. Farmers noted that the number of rice cycles per year depends on a variety of factors, including water availability in the reservoirs in the wet season, whether the farmer decides to grow additional rice and the proximity of the farm to the main canal. Due to the complexity of representing each of these variables, and the lack of information on field-level rice practices, we developed a simple assumption of one planting per year for the baseline scenario, which, based on input from workshops, is likely the practice of the majority of farmers.

To assess the water availability implications of multiple rice-croppings in the different schemes, future scenarios were developed where rice is grown once, twice, three and four times per year. The same rice cropping pattern is applied across all groups. Table A3 and Figure A1 summarize key details of the four irrigated rice variations assessed in this study.

In the historical period and future baseline conditions, rice is planted once per year during the wet season (Table A3). We assumed that all rice planting was carried out by transplanting, the most common but also more water-intensive method of planting, and that this transplanting takes one month. Effective precipitation was calculated from daily rainfall for 30 years from 1982 to 2011 using a method recommended by both the Japanese government and the Special Assistance Project Implementation (SAPI) for the Cambodian West Tonle Sap Irrigation and Drainage Project. The method follows the below logic.

$$\text{For } p < 5 \text{ mm, EP} = 0$$

$$\text{For } 5 < p < 80\text{, EP} = p * 0.8$$

$$\text{For } p > 80 \text{ mm, EP} = 64 \text{ mm}$$

where p = daily precipitation, EP = effective precipitation.

Fields are flooded for planting such that flooded depth equals 3 cm for the first month of transplanting; then, fields are filled to 20 cm over three days and a depth of 20–40 cm is maintained until harvest (Table A3, Figure A1). If flooded depth drops below 20 cm, irrigation will be required to fill fields to 20 cm, but fields can fill up to 40 cm during precipitation events while rice is growing due to an assumed 40 cm tall berm surrounding fields. Each group's planting date is separated by 3 days from the previous group so that planting dates for each rice cycle are spread across approximately one month.

3.1.4. Climate Inputs

Table 2 summarizes the climate input data used for both the historical conditions and the future scenarios in the model. For precipitation input data, twelve rainfall stations were selected based on proximity to the basin and data availability (Figure 1). The Thiessen polygon method was used to calculate daily rainfall from 1985 to 2017 for each catchment for available station data.

Temperature and humidity are not measured as consistently or in as many locations as rainfall. There were only four stations close to the basin and only the Pochentong station had data for temperature, relative humidity and pan evaporation for 22 years. Temperature data of all four stations were compared and found to be relatively similar, implying little spatial difference in temperature across the area (Figure A2), consistent with the understanding that temperatures are relatively uniform across Cambodia [1]. Therefore, the temperature data from the Pochentong station were used from 1996 to 2017 for all catchments and data from the Princeton Global Meteorological Forcing Dataset [38], for the grid cell that overlays the Pochentong station, were used for 1985–1995 (Table 2).

For relative humidity, the observed data of Pochentong from 1996 to 2017 were used for all catchments and the average daily values calculated from the available data were used for 1985–1995. The Princeton Global Meteorological Forcing Dataset was used for wind speed for the years 1985–2010, and because this dataset is only available up to 2010, average daily values calculated from the available data were used for 2010–2015. For cloud coverage, average monthly estimates from the International Water Management Institute World Water and Climate Atlas (IWMI) at the location of the Kampong Thmar station were used (Table 2).

Table 2. Meteorological data source used as input to the Stung Chinit WEAP model.

<table>
<tr><th>Period</th><th>Rainfall</th><th>Temperature</th><th>Relative Humidity</th><th>Wind Speed</th><th>Cloud Coverage</th></tr>
<tr><td>1985–1995</td><td rowspan="3">Thiesen polygon method using observed data from different stations</td><td>Princeton data at Pochentong station [38]</td><td>Weekly average observed data from Pochentong station</td><td rowspan="2">Princeton data [38]</td><td rowspan="4">IWMI estimates [39]</td></tr>
<tr><td>1996–2010</td><td rowspan="2">Observed data of Pochentong station</td><td rowspan="2">Observed data of Pochentong station</td></tr>
<tr><td>2010–2017</td><td>Weekly average Princeton data [38]</td></tr>
<tr><td>2019–2099</td><td>3 RCMs with 2 RCPs each and historical</td><td>3 RCMs with 2 RCPs each and historical</td><td>Weekly average observed data from Pochentang station</td><td>Weekly average Princeton data [38]</td></tr>
</table>

The 2013 Intergovernmental Panel on Climate Change Assessment Report defined four representative concentration pathways (RCPs) that specify concentrations and corresponding emissions of greenhouse gases and are identified using 21st century stabilized radiative forcing values: 2.6, 4.5, 6 and 8.5 W/m^2 [40]. To assess the impact of climate change on the system, future scenarios were developed with seven future climate projections: by repeating the historical climate on a 30-year cycle (baseline conditions) and variations of two RCPs (4.5 and 8.5). Under RCP 4.5, the global temperature is expected to increase by nearly 2.6 °C, and under RCP 8.5, the global temperature is expected to increase by nearly 4.8 °C [40]. Regional Climate Models (RCMs) simulate atmospheric and land surface processes over limited geographic regions, driven by larger global General Circulation Models (GCMs), and are often used to dynamically downscale these global models to provide a more detailed representation of climate processes in specific regions [40]. The climate change regimes were projected using three RCMs (Table 3). Recent research has shown that RCMs generally perform well over the Mekong basin [26,27,29]; however, errors or biases can be seen when using the data directly from the RCM at the basin level [41], so these data were corrected and scaled down to be used at the watershed level.

Table 3. Regional Climate Models used to develop climate regimes.

<table>
<tr><th>RCM Name</th><th>RCM Description</th><th>Driving GCM</th><th>Parameters</th><th>Simulation</th></tr>
<tr><td>CCAM-ACCESS
CCAM-CNRM
CCAM-MPI</td><td>Commonwealth Scientific and Industrial Research Organization (CSIRO), Conformal-Cubic Atmospheric Model (CCAM)</td><td>ACCESS1.0
CNRM-CM5
MPI-ESM-LR</td><td>Rainfall, Max and Min Temperatures</td><td>Historical Run: 1985–2005
Future Run: 2006–2099
RCP Scenarios: RCP 4.5 and RCP 8.5</td></tr>
</table>

Temperature and precipitation data from each climate scenario (RCP 4.5 and 8.5) and each RCM were extracted at station locations and were corrected using the linear scaling bias correction technique [28,42] (Equations (1)–(4)). No process was used to project relative humidity, wind speed and cloud coverage, so multiannual average weekly values from historical data were used in the future scenarios.

$$P_{his}(d)* = P_{his}(d)\cdot\ [\mu_m(P_{obs}(d))/\mu_m(P_{his}(d))] \quad (1)$$

$$P_{sim}(d)* = P_{sim}(d)\cdot\ [\mu_m(P_{obs}(d))/\mu_m(P_{his}(d))] \quad (2)$$

$$T_{his}(d)* = T_{his}(d) + [\mu_m(T_{obs}(d)) - \mu_m(T_{his}(d))] \quad (3)$$

$$T_{sim}(d)* = T_{sim}(d) + [\mu_m(T_{obs}(d)) - \mu_m(T_{his}(d))] \quad (4)$$

where P = precipitation, T = temperature, d = daily, μ_m = long-term monthly mean, * = bias corrected, *his* = raw RCM data, *obs* = observed data and *sim* = raw RCM future data.

3.1.5. Reservoirs and Irrigation Schemes

The Taing Krasaing and Stung Chinit reservoirs are used mainly for irrigation to supply water to the irrigation groups. Both systems are represented in the model, as shown in Figure 4, and connected such that the Stung Chinit can deliver water to the Taing Krasaing, but not vice versa. According to a field visit, this is accurate even if it is physically possible for water to flow both ways in the canal. The Stung Chinit reservoir and system was first built between 1975 and 1979 and was later rehabilitated as a part of the Stung Chinit Irrigation and Rural Infrastructure Project, implemented from 2001 to 2008 [43,44]. Once the project was completed, there was a transition of management from the Ministry of Water Resources and Meteorology (MOWRAM) to provincial- and local-level authorities. Currently, the Provincial Department of Water Resources and Meteorology (PDOWRM) manages the reservoir and any releases into the canals, while Farmer Water User Communities (FWUCs) manage and maintain the canals and distribution to fields [45].

As the Stung Chinit reservoir has been in operation longer, more information was available about its characteristics. Local experts explain that prior to rehabilitation, the spillway of the reservoir was not controlled, and therefore, for most years, the reservoir did not effectively hold water. It is assumed this reservoir is not active in the model until 2007. Multiple documents give various estimates of the volume of the Stung Chinit reservoir, ranging from 7.7 to 41 million m^3 [45]. It seems likely that the discrepancy is between dead storage and minimum supply level storage, as shown in Table 4. We assumed that maximum reservoir volume in the model is set to the full supply level, with dead storage set to minimum supply level (Table 4). The useable storage in the model is 9,340,409 m^3 (Table 4).

According to the Asian Development Bank, the construction of the Taing Krasaing reservoir was started during the period 1975–1978, underwent rehabilitation in 2000 and had partial sections improved and modernized in 2005 and 2012 [46]. We assumed that the reservoir was not delivering water to its command areas until 2017 (Table 1). We assumed a volume of 7,000,000 m^3 for the Taing Krasaing reservoir [46]. The volume elevation curve for both reservoirs is calculated as a linear interpolation between the values in Table 4.

As previously discussed, FWUCs may supply irrigation water in their canals in different ways. Due to the lack of detailed information about each system and its operations, the representation of the eight groups in the model is simplified. All groups have the same priority, meaning that, when shortages occur, the shortage is distributed equally among the groups.

Seepage in canals and on fields is a major loss of water that could be used for irrigation. We model evaporation from both reservoirs based on a modification of the Hargreaves equation and seepage in fields based on soil moisture and assumed sandy loam soil type. Loss due to percolation in the canals is not incorporated into the model due to lack of information. Reservoirs contain the same assumptions in the historical and future scenarios, except that they are always active in the future scenarios.

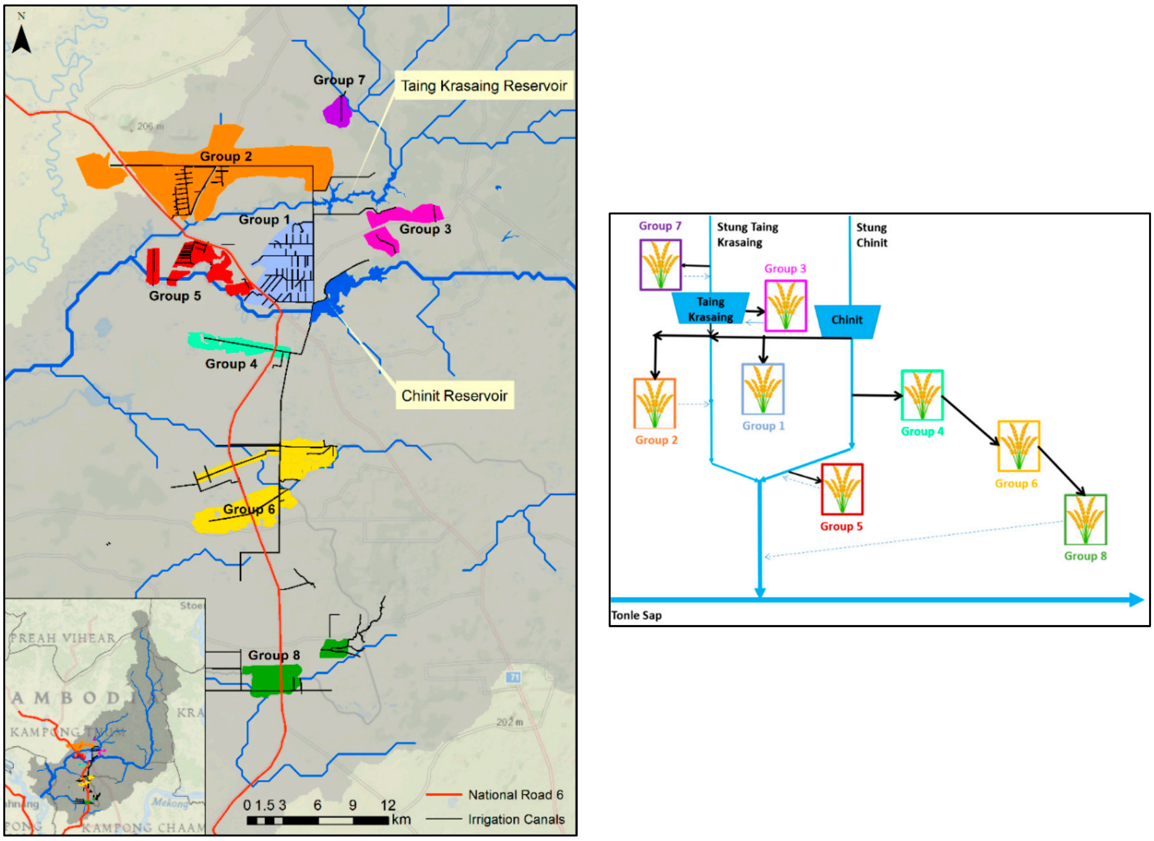

Figure 4. Map of Chinit and Taing Krasaing reservoirs and irrigation schemes (**left**). Inset map shows the entire Stung Chinit watershed, in grey. Schematic of Chinit and Taing Krasaing reservoirs and command area groups (**right**). Canals are represented by black lines, rivers are represented by blue lines and drainage from the fields is shown by the dotted blue lines. Arrows show how each group receives water from the rivers and reservoirs via canals.

Table 4. Characteristics of the two reservoirs represented in the model.

Stung Chinit Reservoir Characteristics [47]	Elevation (m)	Volume (m^3)	Flooded Area (ha)
Empty	248	0	0
Dead storage level	248.3	2,740,000	261.82
Minimum supply level	251.6	26,240,000	1700.94
Full supply level	252	35,580,000	2110.05
Taing Krasaing Reservoir Characteristics [46]			
Minimum supply level	9.08	0	Unknown
Full supply level	16.4	7,000,000	Unknown
Maximum capacity of canal		84.5 m^3/s	

3.1.6. Domestic Water Use

All of the villages within each of the 12 non-irrigated catchments are combined into one demand node per catchment. Information on the population of each village in the Stung Chinit watershed, and their water source for domestic water, was derived from the 2008 General Population Census of Cambodia Map Layer, which gives the location of each village, its population in 2008 and the number of different water source types that the villages uses for supply [48]. This information was summed across the cluster of villages located within each of the catchments. In the model, the population of the demand node stays constant from 1985 to 2008 and is based on the census data in 2008. It is interpolated between 2008 and 2015 based on population data for 2014–2015. We assumed a water use rate of 65 L per capita per day based on the Food and Agriculture Organization of the United Nations recommendations for rural water use in Cambodia.

Based on the census data, most villages rely heavily on groundwater for their water supply but also use water from a combination of surface water and sources indicated as "other/purchased" on the 2008 census. (Groundwater in this study is the combination of the census categories "tube/pipewell", "protected dug well", "unprotected dug well"; surface water is the census category "spring, river, stream, etc." and other is the combination of the census categories "bought" and "other". Collection of rainwater is not included in the model. Because, for the census category "piped", the source of the piped water was unknown, it was assumed that all households using piped water received it from groundwater, the most common source overall.) For each demand node, the percentage of its demand that is met by groundwater, surface water or another source was calculated as the number of households within that group of villages that use each source type, divided by the total number of households (Table A4). Each catchment in the model has its own groundwater object as a water source, takes water from the river reach within the catchment and/or from another bottomless source representing the use of purchased or bottled water. Demands representing villages receive water from surface water bodies before irrigation demands receive water.

In all future scenarios, domestic demand grows at the growth rate calculated from population data in 2008 and 2016, for each village.

3.2. Calibration

The Stung Chinit model is calibrated during the historical period against measured streamflow, reference evapotranspiration (ET) and deep percolation estimates; estimates of evaporation from reservoirs and irrigation demand have been compared with other studies. Streamflow was calibrated at the streamflow gauge on the Stung Chinit, just downstream of the Stung Chinit reservoir (Figure 1). The calibration was conducted from 1997 to 2005 (Table 5, Figure 5) based on the assumption that the Stung Chinit reservoir was not fully operating during this time period and the streamflow at the gauge was unimpaired.

Table 5. Final parameter values and goodness of fit statistics for streamflow calibration.

Variable	Land Use Category	Value	Units
Deep Conductivity	All	100	mm/week
Deep Water Capacity	All	300	mm
Crop Coefficient (kc)	All	1.1	NA
Root Zone Conductivity	All	35	mm/week
Runoff Resistance Factor	Non-Irrigated Rice	9	NA
	Barren or Sparse Vegetation	15	NA
	Forest	24	NA
	Pasture	18	NA
	Plantation	12	NA
	Urban	6	NA
	Water	30	NA
	Wetland	30	NA
Preferred Flow Direction	All	0.85	NA
Soil Water Capacity	Non-Irrigated Rice	300	mm
	All other categories	700	mm
Nash–Sutcliffe efficiency (NSE)	**R^2**	**Percent Bias**	**Root Mean Squared Error (RMSE) (m^3/s)**
0.81	0.8	19	31.94

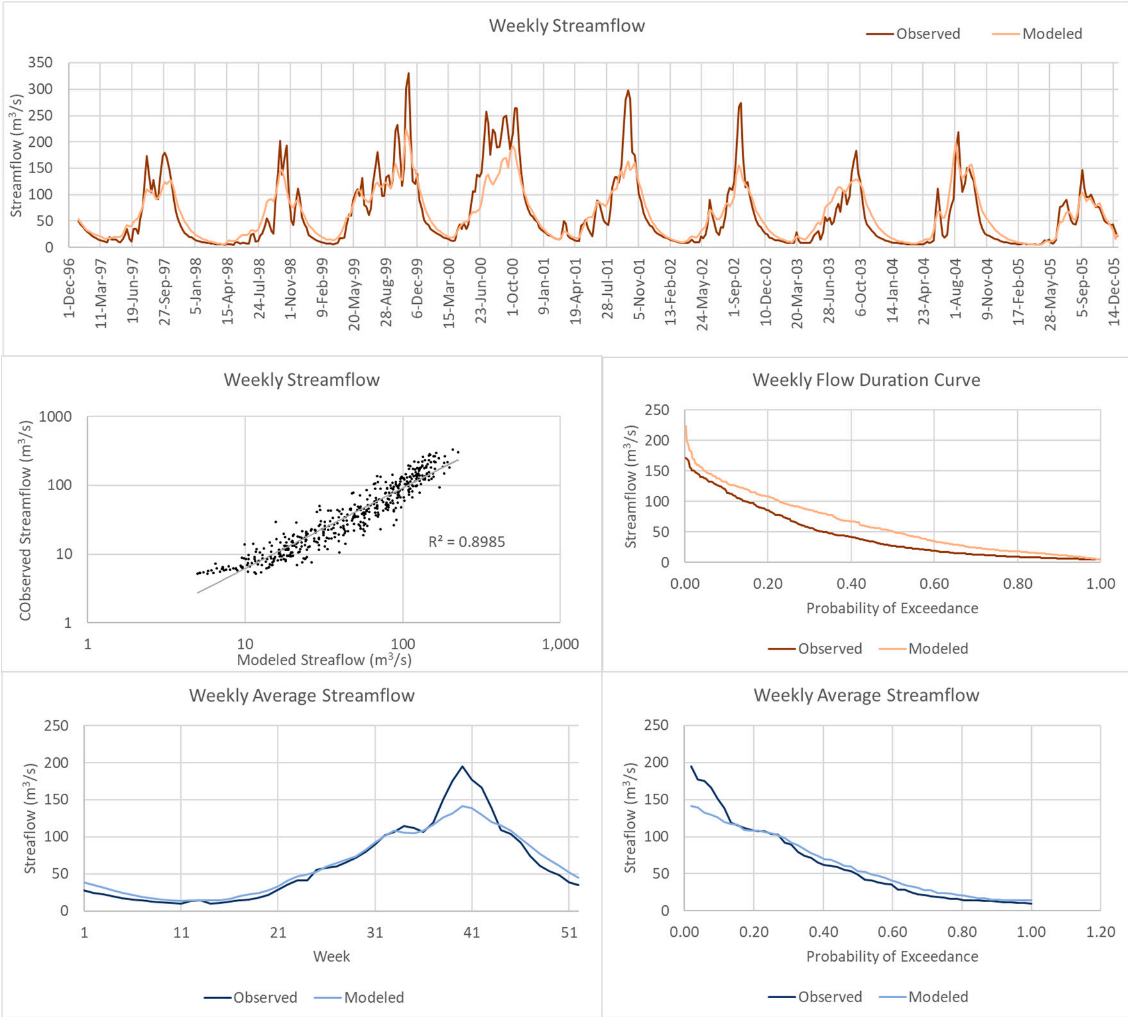

Figure 5. Graphs showing the streamflow calibration of the Stung Chinit model.

There is no streamflow gauge on the Taing Krasaing river, but flows have been estimated in the Taing Krasaing Irrigation System Feasibility Study [46]. In the feasibility study, average wet season peak flows are estimated as 50 m^3/s compared to approximately 40 m^3/s in the Stung Chinit WEAP model. Average low flows are estimated close to 0 m^3/s in the feasibility study and 2–3 m^3/s in the WEAP model [46].

Average monthly reference evapotranspiration (ET) from the Stung Chinit model (averaged 1997–2007) was compared against estimates for reference: ET from the International Water Management Institute World Water and Climate Atlas (IWMI) at the location of the Kampong Thmar streamflow gauge as well as measured pan evaporation, measured at the Pochentang climate station (Figure 6) [39]. This comparison demonstrates that reference ET from the WEAP model is within the range of other estimates.

Lastly, WEAP outputs for deep percolation, evaporation from reservoirs and irrigation demand were compared with estimates from various studies conducted within the Stung Chinit watershed and largely found to be reasonable to validate the WEAP model, as shown in Table A5.

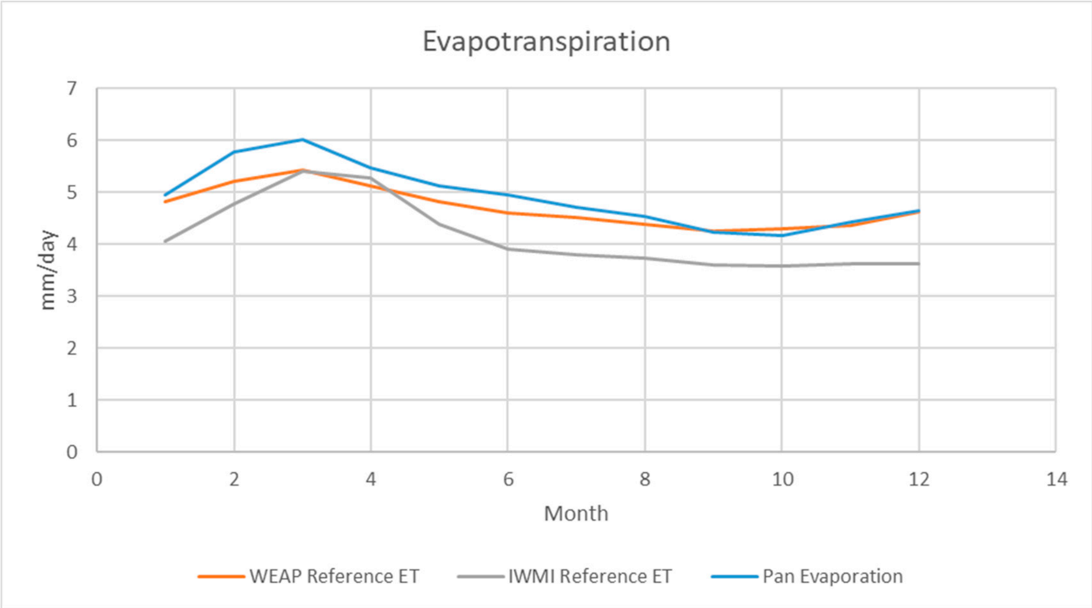

Figure 6. WEAP reference Evapotranspiration (ET) comparison with other estimates.

3.3. Scenario Analysis

The Stung Chinit WEAP model was used to analyze a suite of future scenarios regarding rice farming practices and alternately prioritizing water for irrigation and water for aquatic species habitat in the lower part of the basin downstream of the two reservoirs. These different management practices were assessed under seven different climate projections. In total, 112 scenarios were analyzed in the model, the result of every combination of climate projections and management strategies listed in Table 6, over the years 2019–2099.

The detailed assumptions for incorporating climate change, rice crop schedules and increasing irrigated area into the future scenarios are described in Sections 3.1.2–3.1.4, respectively. In order to assess the tradeoffs between primarily using water for agriculture production and ensuring sufficient water for aquatic habitat, we implemented a flow requirement just downstream of the last canal diversion for irrigation (Figure 7). The requirement for each month is the 95th percentile flow, assessed across all flows in the record for that month.

In scenarios with variation FR_Q95 (Table 6), the flow requirement has the highest priority over all demands. This means that, in times of shortage, water is sent downstream to meet the flow requirement, and only if the entire requirement is met can water be diverted for other uses. In all other scenarios, water is only sent downstream if all other demands are met and the reservoirs are full.

Table 6. Climate projections and management strategies incorporated into the model to develop 112 scenarios.

Climate Projections	
Projection Name	**Description**
Historical	Historical climate, repeated into the future
ACCESS 4.5	RCM ACCESS, RCP 4.5
CNRM 4.5	RCM CNRM, RCP 4.5
MPI-ESM-LR 4.5	RCM MPI-ESM-LR, RCP 4.5
ACCESS 8.5	RCM ACCESS, RCP 8.5
CNRM 8.5	RCM CNRM, RCP 8.5
MPI-ESM-LR 8.5	RCM MPI-ESM-LR, RCP 8.5

Table 6. *Cont.*

Management Strategies			
Strategy Name	**Rice Crop Schedule**	**Increase Irrigated Area**	**Prioritize Different Demands**
S00 R_1x	Wet season rice	Maintain irrigated area at max size in 2018 for all irrigation schemes	During shortages, ensure supply to irrigation as first priority. No flow requirement implemented.
S01 R_2x	Early wet season, wet season rice		
S02 R_3x	Early wet season, wet season, dry season rice		
S03 R_4x	Four rice crops per year		
S04 R_1x A_+10%	Wet season rice	Increase area of all irrigation schemes by 10%	
S05 R_2x A_+10%	Early wet season, wet season rice		
S06 R_3x A_+10%	Early wet season, wet season, dry season rice		
S07 R_4x A_+10%	Four rice crops per year		
S08 R_1x FR_Q95	Wet season rice	Maintain irrigated area at max size in 2018 for all irrigation schemes	During shortages, ensure 95 percentile flow downstream of irrigation diversions as first priority.
S09 R _2x FR_Q95	Early wet season, wet season rice		
S10 R_3x FR_Q95	Early wet season, wet season, dry season rice		
S11 R_4x FR_Q95	Four rice crops per year		
S12 R_1x A_ + 10% FR_Q95	Wet season rice	Increase area of all irrigation schemes by 10%	
S13 R_2x A_ + 10% FR_Q95	Early wet season, wet season rice		
S14 R_3x A_ + 10% FR_Q95	Early wet season, wet season, dry season rice		
S15 R_4x A_ + 10% FR_Q95	Four rice crops per year		

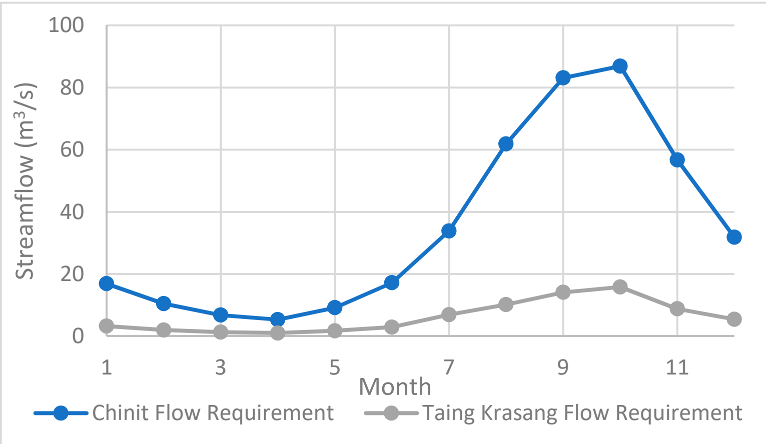

Figure 7. Monthly streamflow requirements downstream of irrigation schemes.

4. Results

4.1. Climate Change in the Stung Chinit Watershed

Global climate change will have two major impacts on the Stung Chinit watershed according to the three regional climate models (RCM) under two representative climate pathways (RCPs): (1) to increase long-term temperature averages during the century, and (2) to increase precipitation volatility. Figure 8 shows a rolling three-year average of monthly averaged temperatures to illustrate longer-term temperature trends without the slight seasonality from month to month. In all three of the maximum, average and minimum daily temperature datasets, the six climate scenarios are observed to start off close together at the beginning of the modeled period and separate into three groups at the end of the century according to RCP. The RCP 8.5 scenarios show the highest end of century temperatures, with RCP 4.5 below that and historical temperatures showing no increase. The RCP 8.5 scenarios show temperature increases in the minimum and average temperature datasets that bring them up to the level of the historical average and maximum temperature datasets towards the end of the century.

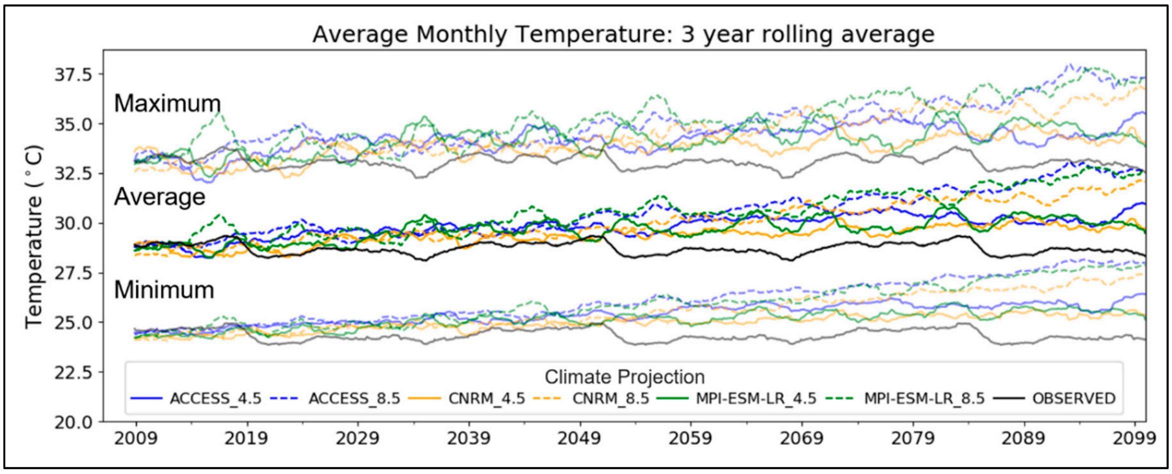

Figure 8. Downscaled temperature projections for Phnom Penh station showing a rolling three-year average of monthly averaged daily minimum, average and maximum temperatures.

All six climate scenarios exhibit a ten-year rolling average annual rainfall of less than the lowest historical ten-year average at least once during the next century, except the CNRM and MPI-ESM-LR models at RCP 8.5 (Figure 9a). The ACCESS model shows the greatest volatility of precipitation in the long term for both RCPs and the MPI-ESM-LR shows the largest increases in long-term averaged precipitation for both RCPs. An important change is noticeable in the distribution of daily precipitation values on rainy days (Figure 9b) and the total number of rainy days both in the wet and dry season (Figure 9c). Specifically, all scenarios show more rainy days in both the wet and dry season than the historical dataset (Figure 9c). However, the rainy days are skewed toward less rain on the days that do rain, except for a few extremely wet days, in comparison with the historical (Figure 9b).

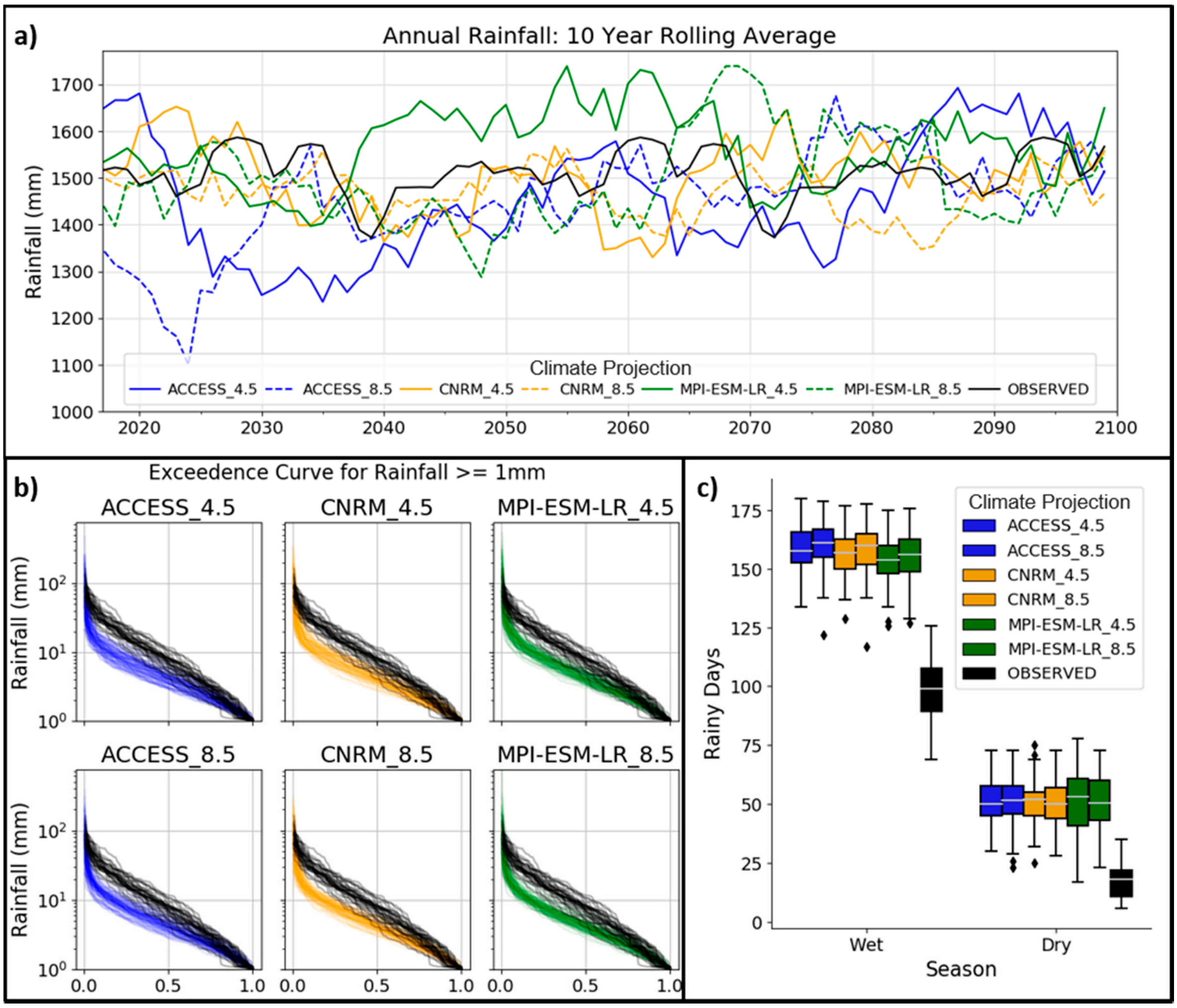

Figure 9. Statistical analysis of downscaled precipitation projections for Catchment 1: (**a**) Rolling ten-year average of total annual precipitation; (**b**) annual exceedance curve for daily precipitation of at least 1 mm for climate scenarios (blue, orange and green) 2019–2099 and historical (black) 1985–2019; (**c**) box plots for number of rainy days per year in the wet and dry season.

4.2. Comparison of Water Demands

Considering average weekly water demands for irrigated rice and for maintaining environmental flow requirements, the demand for irrigation is typically small relative to the demand for the flow requirement (Figure 10). During the wet season (approximately weeks 20–52), the demand for rice is small relative to the required streamflow and flows available upstream, especially when crops are growing and flooding is being maintained, after the initial and second flooding (Figure 10). While strategy 00 shows that the demand for initial flooding of fields plus the streamflow requirement is larger than the available water in the two rivers, this is a relatively short period of time and there is water available in the reservoirs to compensate (Figure 10a).

During the dry season (approximately weeks 1–20), the demand for initial flooding, as well as the demand to maintain flooding depths while the crop is growing, is larger than the minimum flow requirement and, together with the minimum flow requirements, exceeds flows upstream (Figure 10). When this occurs, there is not sufficient water in the reservoirs to compensate, and the reservoirs are completely drained (Figure 10b).

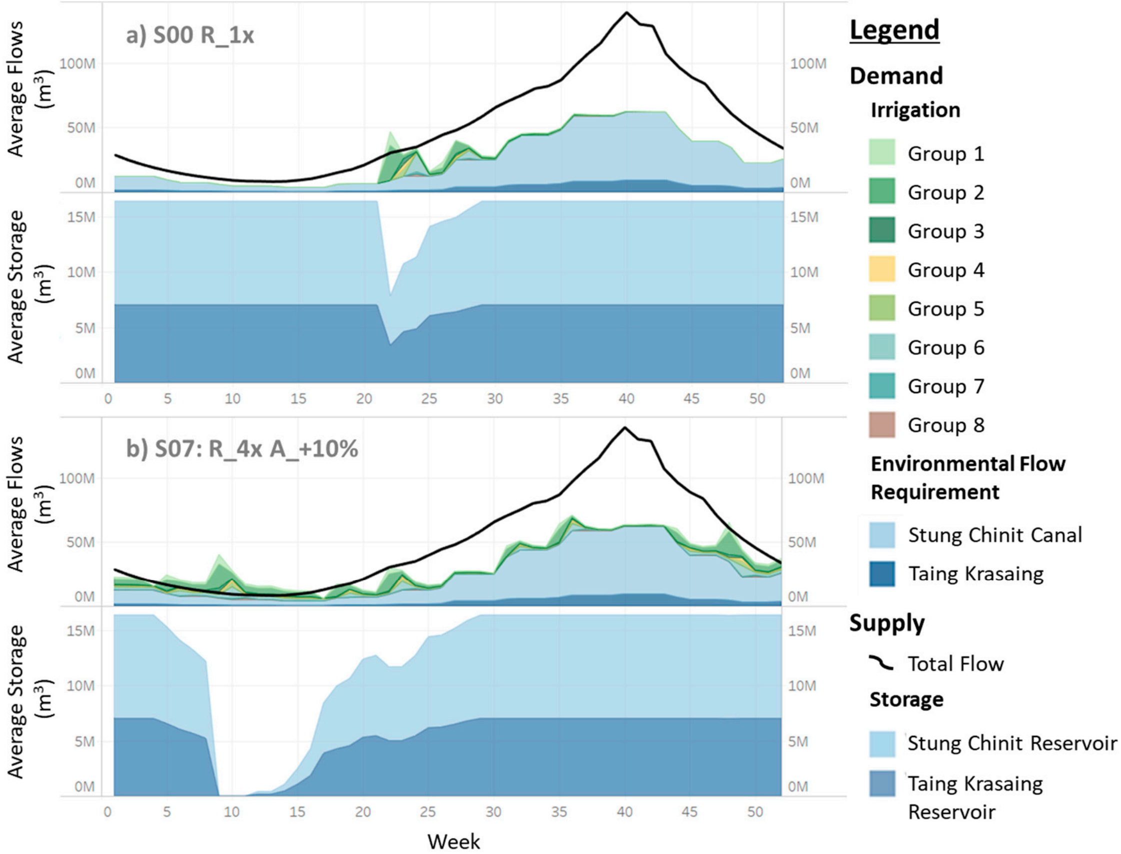

Figure 10. (**a**) Comparison of average weekly flow available in the Stung Chinit and Taing Krasaing rivers with total demands (top) and average reservoir volume in the Taking Krasaing and Stung Chinit reservoirs (bottom) with historical climate and Strategy S00. (**b**) Same as (**a**), for historical climate and strategy S07 R_4x A_+10%. An interactive graphic with all strategies and climate scenarios can be accessed here: https://public.tableau.com/views/JournalArticleVisualizationStungChinitWatershedCambodia/Story1?:language=en&:display_count=y&publish=yes&:origin=viz_share_link.

4.3. Irrigation and Streamflow Coverage

Coverage, as used here, is the percentage of a demand that is met in a given time period. Annual coverage of rice is the annual demand that is met, over the course of the entire year, calculated across all rice plantings, averaged across all groups. Annually, rice coverage is high, reaching approximately 100% in all years when rice is planted once per year (Strategy 00, Figure 11). In the most extreme scenario, where rice demand is highest (S15, 4 crop plantings, increase irrigated area by 10% and when environmental flows are prioritized), rice coverage is less than 100% in some years, but overall there are few years where coverage is below 50% (Figure 11).

Annual coverage is a useful measure of irrigation shortages as timing of irrigation can sometimes be managed, but it is important to assess the annual demand and supply to evaluate the viability of the crop planting strategy. If some weeks have less irrigation, this can be compensated for in other weeks, to an extent, and the crop will still survive, depending on how extreme and how often the shortages are.

Annual coverage is less useful when assessing streamflow requirements as the timing of flows is essential to maintaining habitats and ecosystems, and more water in some weeks cannot compensate for less in others. Figure 12 shows average weekly coverage of streamflow requirements in the two rivers downstream of all irrigation diversions. Shortages, as used here, are periods when coverage is less than 100% or supply is less than demand in a given time period. Across all scenarios when the flow requirement is not prioritized, there are shortages, particularly when fields are being flooded and during the dry season. Dry season shortages are severe, where there is on average no water in the rivers for multiple weeks in a row (Figure 12). These severe shortages last longer in the Taing Krasaing, a smaller river (Figure 12), and are more severe in S07 when rice is grown four times and the irrigated area is expanded by 10%. Peaks in total flows correspond to periods where fields are draining for harvest (Figure 12, particularly in the Taking Krasaing). In the Taing Krasaing, the size of the peaks relative to the flows before and after the peaks show the volume of water in the fields (which are contributed to the river when fields are drained) and the flows in the river (Figure 12). Draining the fields may double or nearly triple the flows in the river.

While significant shortages did not occur for annual irrigation coverage, when considering coverage at a weekly scale, there are many weeks, and even many consecutive weeks, when demand coverage of rice is below 50% when rice is planted four times per year (Figure 13, left, b). These shortages become more severe when streamflow requirements are prioritized (Figure 13, left, d). However, for rice irrigation, across all scenarios, there are almost no weeks when coverage is less than 5% (e.g., nearly no water that is required is supplied to the demands, Figure 13, right).

The opposite situation is occurring for streamflow, when assessed at the weekly timestep. At the weekly scale, when no flow requirement is implemented, there are often many weeks, and consecutive weeks where less than 50% of the flow requirement is met (Figure 13, left, a,b) and many less than 5% of the flow requirement is met (essentially no water in the rivers, Figure 13, right, a,b) when no flow requirement is implemented.

Even when rice is only planted once per year, there are many weeks with <5% coverage in the Taking Krasaing (Figure 13, right, a).

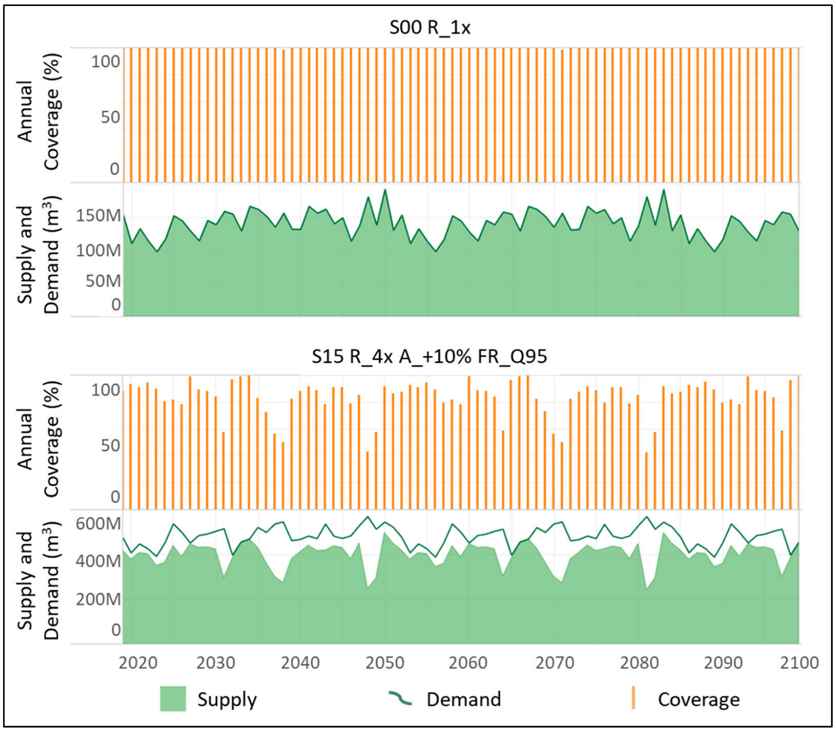

Figure 11. Annual coverage and comparison of annual rice irrigation demand (dark green line) and supply (light green area) for S00 and S15, with historical climate. An interactive graphic with all strategies and climate scenarios can be accessed here: https://public.tableau.com/views/JournalArticleVisualizationStungChinitWatershedCambodia/Story1?:language=en&:display_count=y&publish=yes&:origin=viz_share_link.

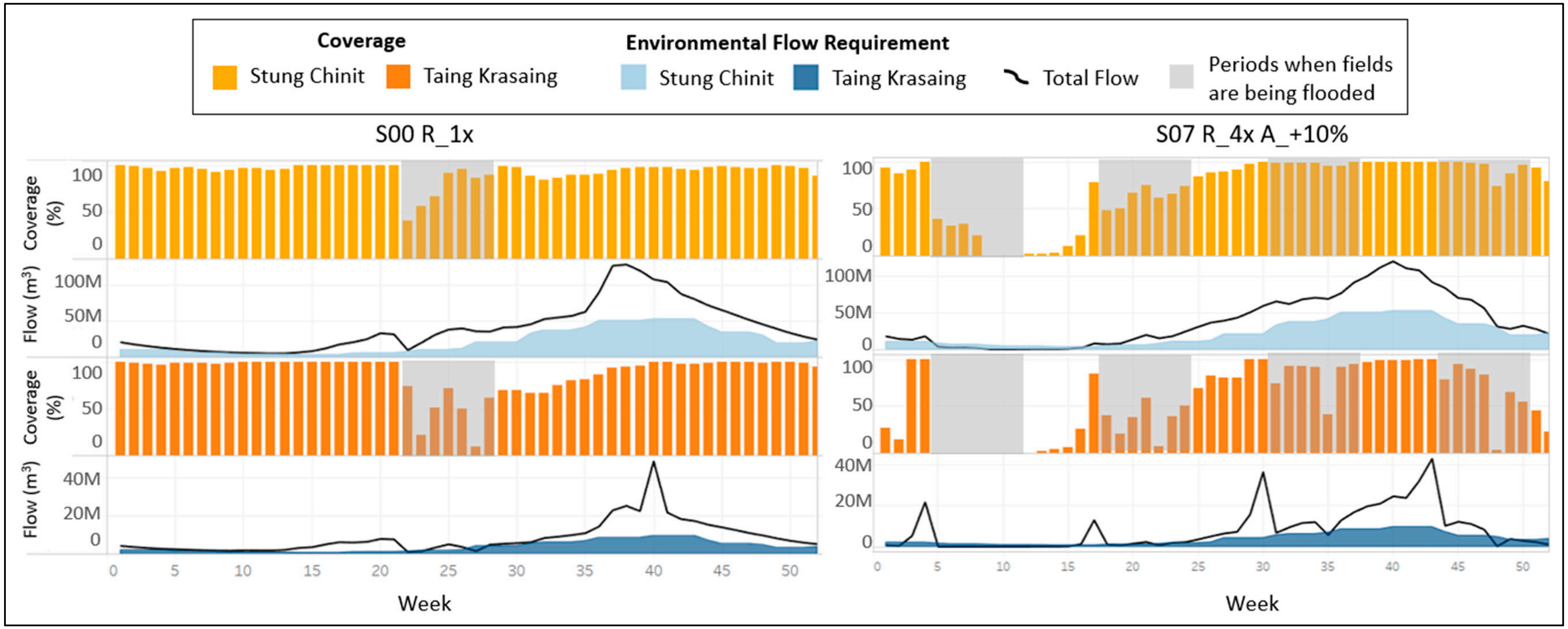

Figure 12. Average weekly coverage of flow requirements in the Stung Chinit and Taking Krasaing and comparison of the flow required (blue shaded area) and flow in the river (black line) downstream of the irrigation diversions. Where the black line dips into the blue shaded area, the flow requirement is not met. Strategies S00 and S07 are shown, both with historical climate. An interactive graphic with all strategies and climate scenarios can be accessed here: https://public.tableau.com/views/JournalArticleVisualizationStungChinitWatershedCambodia/Story1?:language=en&:display_count=y&publish=yes&:origin=viz_share_link7.

Figure 13. Consecutive weeks of rice and streamflow shortages (defined as a week where coverage is below the coverage criteria). Where each bar exists, a shortage occurred in that week. Where bars are greater than 1, this is the cumulative number of weeks since a shortage did not occur. Strategies S00, S07, S08, S15 are shown, all with historical climate and coverage criteria = 50% (**left**) and 5% (**right**). An interactive graphic with all strategies and climate scenarios can be accessed here: https://public.tableau.com/views/JournalArticleVisualizationStungChinitWatershedCambodia/Story1?:language=en&:display_count=y&publish=yes&:origin=viz_share_link.

4.4. Tradeoffs between Different Water Uses

Figures 14 and 15 show the average number of weeks per year where shortages occur, across all strategies and all climate projections, presenting the results from all 112 scenarios. Vulnerability estimations based on water shortages are used to evaluate tradeoffs based on Forni et al. [49]. Overall, there is more variation in vulnerabilities between strategies (between columns) than between climate scenarios (between rows). Planting rice more than twice per year without a flow requirement enforced (S02, 03, 06, 07) causes severe shortages in both rivers—more than 6 weeks with less than 5% of the flow requirement, essentially no water in the Stung Chinit, and more than 15 weeks of shortages in the Taking Krasaing (Figure 15). Planting rice more than twice per year while implementing a flow requirement results in 7–20 weeks per year on average with less than 50% of the irrigation coverage (Figure 15, S10, S11, S14, S15). However, there are very few weeks with irrigation coverage less than 5% in these same scenarios (Figure 15). The impact on rice of prioritizing flow requirements is less than the impact on flow requirements of prioritizing rice.

Legend: 0-6 | 7-13 | 14-20 | 21-28

50% Coverage Criteria — Average Number of Weeks per Year Below Threshold

Metric	Climate Projection	S00	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10	S11	S12	S13	S14	S15
Rice Irrigation	Historical	0	0	1	2	0	0	2	2	1	2	9	9	1	2	10	10
	ACCESS 4.5	0	0	1	2	0	0	2	2	4	7	15	15	4	7	16	16
	CNRM 4.5	0	0	1	2	0	0	1	2	3	5	13	13	3	6	14	14
	MPI-ESM-LR 4.5	0	0	1	1	0	0	1	2	3	4	12	13	3	5	13	14
	ACCESS 8.5	0	0	1	2	0	0	2	2	2	5	13	13	2	5	14	14
	CNRM 8.5	0	0	1	2	0	0	1	2	2	5	14	14	2	5	14	15
	MPI-ESM-LR 8.5	0	0	1	2	0	0	2	3	3	4	13	14	3	5	14	15
Stung Chinit	Historical	2	4	14	14	3	5	15	15	0	0	0	0	0	0	0	0
	ACCESS 4.5	3	5	16	16	4	6	17	17	0	0	0	0	0	0	0	0
	CNRM 4.5	3	5	15	15	3	6	16	17	0	0	0	0	0	0	0	0
	MPI-ESM-LR 4.5	2	4	14	14	3	4	15	15	0	0	0	0	0	0	0	0
	ACCESS 8.5	2	5	15	15	3	5	16	16	0	0	0	0	0	0	0	0
	CNRM 8.5	3	5	16	16	3	6	17	17	0	0	0	0	0	0	0	0
	MPI-ESM-LR 8.5	2	4	15	15	3	5	16	17	0	0	0	0	0	0	0	0
Taing Krasaing	Historical	3	6	18	19	3	7	20	21	0	0	0	0	0	0	0	0
	ACCESS 4.5	4	6	18	19	4	7	19	20	0	0	0	0	0	0	0	0
	CNRM 4.5	3	7	18	19	4	8	19	20	0	0	0	0	0	0	0	0
	MPI-ESM-LR 4.5	3	6	18	19	3	7	19	20	0	0	0	0	0	0	0	0
	ACCESS 8.5	3	6	17	18	3	6	18	19	0	0	0	0	0	0	0	0
	CNRM 8.5	3	7	18	20	3	7	19	21	0	0	0	0	0	0	0	0
	MPI-ESM-LR 8.5	3	6	18	19	4	7	19	21	0	0	0	0	0	0	0	0

Figure 14. Average number of weeks per year where coverage is less than 50% coverage criteria.

Legend: 0-6 | 7-13 | 14-20 | 21-28

5% Coverage Criteria — Average Number of Weeks per Year Below Threshold

Metric	Climate Projection	S00	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10	S11	S12	S13	S14	S15
Rice Irrigation	Historical	0	0	0	0	0	0	0	0	0	1	1	2	0	1	2	2
	ACCESS 4.5	0	0	0	0	0	0	0	0	2	4	6	6	3	4	6	6
	CNRM 4.5	0	0	0	0	0	0	0	0	2	3	5	5	2	3	5	5
	MPI-ESM-LR 4.5	0	0	0	0	0	0	0	0	2	2	4	4	2	3	4	4
	ACCESS 8.5	0	0	0	0	0	0	0	0	2	3	5	5	2	3	5	5
	CNRM 8.5	0	0	0	0	0	0	0	0	1	2	4	4	1	3	4	5
	MPI-ESM-LR 8.5	0	0	0	0	0	0	0	0	2	2	4	4	2	2	4	5
Stung Chinit	Historical	1	3	12	11	2	3	13	12	0	0	0	0	0	0	0	0
	ACCESS 4.5	1	2	12	11	2	3	14	12	0	0	0	0	0	0	0	0
	CNRM 4.5	1	3	12	11	2	3	13	12	0	0	0	0	0	0	0	0
	MPI-ESM-LR 4.5	1	2	12	11	1	2	13	12	0	0	0	0	0	0	0	0
	ACCESS 8.5	1	2	12	11	1	3	13	12	0	0	0	0	0	0	0	0
	CNRM 8.5	1	3	13	12	1	3	14	13	0	0	0	0	0	0	0	0
	MPI-ESM-LR 8.5	1	2	13	11	1	2	14	12	0	0	0	0	0	0	0	0
Taing Krasaing	Historical	3	6	18	19	3	7	20	21	0	0	0	0	0	0	0	0
	ACCESS 4.5	4	6	18	19	4	7	19	20	0	0	0	0	0	0	0	0
	CNRM 4.5	3	7	18	19	4	8	19	20	0	0	0	0	0	0	0	0
	MPI-ESM-LR 4.5	3	6	18	19	3	7	19	20	0	0	0	0	0	0	0	0
	ACCESS 8.5	3	6	17	18	3	6	18	19	0	0	0	0	0	0	0	0
	CNRM 8.5	3	7	18	20	3	7	19	21	0	0	0	0	0	0	0	0
	MPI-ESM-LR 8.5	3	6	18	19	4	7	19	21	0	0	0	0	0	0	0	0

Figure 15. Average number of weeks per year where coverage is less than 5% coverage criteria.

5. Discussion

5.1. Vulnerability of the Stung Chinit Watershed

While climate change poses a significant threat to the Stung Chinit watershed, on average, when looking at a long-term assessment to the end of the century, vulnerabilities to the system vary more largely between management strategies than within strategies between climate scenarios. Climate change impacts were assessed in this study over the entire projected time period. It is likely that climate change impacts will increase over time and impacts in later years should be compared in future work with impacts to the near-term future. When rice is planted one or two times per year, this study suggests that climate change may be mitigated with irrigation practices, and downstream flows can be protected. However, regardless of climate change, planting rice more than twice per year may lead to significant shortages for both rice crops and stream flows, particularly without protections for stream flows. Stakeholders have already noted the lower flows in the system downstream of the irrigation schemes, impacting fish populations and navigation [18]. This is occurring already in a system where double cropping, let alone multiple cropping, is still uncommon [14].

Given that water shortages for rice irrigation occur as a result of the implementation of many of the strategies, particularly those that include large increases in rice production and/or streamflow protection, it will be important to understand the effects of such shortages on rice yields. A number of studies have shown that drought timing plays an important role in the effects of water shortage on overall yield and can be mitigated by adjusting rice variety, fertilizer application and timing of sowing [50,51]. In this study, the fields were assumed to be flooded to 3 cm during the transplanting and early vegetative stages and to 20 cm during the reproductive and ripening stages of plant development. However, Ikeda et al. showed that direct seeding and dry transplanting may result in higher overall yields with lower water use, while Tabbal et al. showed that lowering of the water table to the land surface or pulse irrigation can mitigate drought conditions [52,53]. Murphy et al. discuss multiple methods of reducing the irrigation requirement for rice that may be particularly important for Cambodia in adapting to and mitigating climate change through reducing methane emissions [21]. Some of these include Alternate Wetting and Drying [54], the System for Rice Intensification [55] and Ground Cover Rice Production Systems [56], to note a few. The analysis conducted here was conservative in assessing the viability of the current and more water-intensive practice, but other practices should be explored to further understand their effectiveness and viability in this system. Other countries in the region are evaluating the potential benefits in adopting new rice cultivars and planting schedules that would help with the increase in rice production while adapting to climate change challenges [57].

In this analysis, significantly fewer weeks where rice experiences <5% coverage occur across the scenarios compared to the streamflow requirement (Figure 13), because rice demands are typically small relative to the streamflow requirement (Figure 10). In other words, even after meeting the streamflow requirement, there is typically at least some water available for rice. Additionally, shortages appear to be most severe in the dry season and during weeks when fields are being flooded (Figure 12). In this analysis, it was assumed that there are 3 days between when each field initially floods their fields (Figure A1). Potentially, fields could be flooded more gradually, over time, or different parts of the system could coordinate to flood more effectively and avoid shortages during this time.

Implementing any of the above-mentioned practices to alleviate water shortages would require coordination both within and between irrigation groups, knowledge sharing between farmers and regional government and updates to on-farm and irrigation group infrastructure. Overall, the purpose of this study is to investigate water availability in the basin over a long period of time and how increased crop cycles may or may not be possible. This study suggests that the system appears to have sufficient water to support at least two rice plantings per year and irrigation expansion of 10% while protecting downstream flows. Some short-term and smaller shortages may be mitigated by coordinated water management practices and different irrigation practices, which would likely include significant coordination by the Farmer Water User Communities (FWUCs).

5.2. Water Management and Inequitable Water Access

While this work suggests that the physical system can support more than one rice planting per year, double cropping, let alone multiple cropping, is still relatively uncommon in the Stung Chinit watershed [14]. In conversations with stakeholders, not all were interested in or able to grow rice more than once or twice per year, for reasons related not to water availability but to water access—or their ability to access water that may be available to them, or in canals near their fields.

Rice farm proximity to tertiary canals and the relative location of rice farms with respect to other users upstream are important spatial aspects affecting water distribution inequalities. Temporal aspects play a key role in the spatial inequalities, as well. For example, rice farmers located upstream may have better access to water than users downstream, particularly during dry months and during years of drought. Situations may occur where flows are too weak and cannot reach the ends of the canal [32], some fields are at too high elevations to receive water despite their proximity [32], and not all farmers can afford to pump water from the canals to their fields or to pay the FWUC dues to use water supplied to the canals [18,32]. Additionally, the schemes in the Stung Chinit watershed only serve small parts of the basin overall.

Addressing water access inequalities at the watershed level requires a closer look at the spatial, temporal, social and economic factors driving the mechanisms and processes of water distribution, access and use as it is highlighted in [20] for the Mekong watershed. While this study looks at water security implications at the watershed level, it allows the examination of the spatial and temporal aspects of water distribution that are crucial to the viability of multiple rice-cropping in the basin. The assumption that all fields within an irrigation scheme have equal access to water if it is in the reservoir or canal near their field, however, may not reflect sufficiently the realities of the system's inequality. This finding agrees with [11] in the sense that there is no single solution for climate change adaptation, and the evaluation of various options that take into account the time and scale differences in the analysis is needed [57].

Affordability aspects also need closer examination. FWUC fees may remain a challenge. In interviewing farmers who belonged to the Stung Chinit FWUC, Sam and Shinogi found that only 55% of farmers are able to pay their dues to the FWUC, meaning that FWUCs rely heavily on government subsidies that may not be available in the future [32]. Expanding the irrigation schemes may provide the FWUCs with more funds, assuming that farmers are able to afford the fees with increased incomes. As indicated by [22], top-down management may not be enough to address the environmental threats and damages. Better water governance coordination and decision-making processes are needed. This is an important aspect suggesting that water access inequalities need to be analyzed beyond the physical and regulatory constraints. A holistic approach that unfolds the governance, social and gender norms and structures, the economic and cultural valuation implications, as well as the physical, spatial and temporal aspects is needed to further examine water resources inequalities and the viability of increasing rice production.

5.3. Future Work

Overall, this work relied on a significant amount of assumptions as data regarding specific planting practices and irrigation use are limited. Almost all of the data used in the development were sourced from national government-level information, with input from some FWUCs, which is typical for hydrologic and water management-related work. However, in an area where water access and availability may be significantly varied due to issues beyond the existence of water in the system, more work should be done to better understand decisions made and issues experienced at the individual famer level. Improving water management capacity and access to resources within the FWUCs will likely be essential to making multiple cropping a reality for more farmers in the Stung Chinit Watershed.

There are several specific areas where the physical representation of the system could be improved as more information becomes available, including:

- A better representation of losses due to infiltration on the fields and canals to better determine actual water availability in the system. Issues with infiltration have been mentioned in previous work, but volumes lost are not well understood [45];
- Assessing how land use change is affecting water availability, particularly due to siltation in the reservoirs, a concern mentioned in stakeholder workshops;
- Improving the representation of the reservoirs and their operations if more data are available;
- Considering different cropping patterns between and within irrigation groups, rather than assuming that all groups plant the same.

6. Conclusions

Due to the relative demands for streamflows and rice in the dry season, if dry season rice planting is widely promoted, this will severely impact streamflows. However, implementing a flow requirement protects these flows, while only causing minor shortages to rice when the wet season growing period is extended by planting rice once or twice per year. These shortages may be alleviated with improved cooperation and management in the river basin and shifting rice irrigation practices. While climate change is a threat, and will lead to warming temperatures and therefore potentially higher demands for rice irrigation, the larger threat to rice and ecosystems appear to be the management (or lack thereof) of the system to prioritize water uses. While this study suggests that there is physically sufficient water to expand the irrigated area, grow rice twice per year and protect downstream flows, this water may not be available to all, and significant management is required to ensure this, which is lacking. It will be important to better understand who can and cannot grow rice multiple times per year, due to impacts beyond water availability. As this study focused largely on availability; management, poverty and other barriers to access may be preventing this system from reaching its full potential, both in protecting ecosystems and providing resilient livelihoods for its people.

Author Contributions: The conceptualization, supervision and project administration of this work were conducted by A.H.-L. and L.F., with funding acquisition provided by A.H.-L. Provision of resources used in this study, including model input data and assumptions for the base model was led by T.S., with support from M.S. and guidance from S.R.B. Data curation, as in preparation of model input data and climate change scenarios, was conducted by S.R.B., M.R.L.M., M.S. and A.M.M. Software and methodology (WEAP model development) and the formal analysis and investigation conducted with the WEAP model was led by S.R.B., with the support of M.S., T.S., M.R.L.M., A.M.M. and E.G. Visualizations of model results and outputs were prepared by S.R.B., L.F. and M.R.L.M. The writing—original draft preparation—of this article was prepared by S.R.B. and M.R.L.M. and the writing—review and editing—was conducted by L.F., A.H.-L., M.S., A.M.M., E.G. and T.S. Validation of the work was attained through workshops where the research methods and results were presented to local stakeholders. Authors who contributed to the preparation and facilitation of workshops are T.S., L.F., S.R.B., M.S. and A.H.-L. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Table A1. Characteristics of 20 catchments in the Stung Chinit model, the WEAP method used to calculate rainfall-runoff and irrigation demand, whether or not the catchment is irrigated, the river the catchment contributes to (primarily, secondarily, if it does not contribute directly to one of the main rivers), whether or not it is upstream of the streamflow gauge and its area in 2017.

Catchment Name	WEAP Method	Irrigated?	River	Upstream of Gauge?	Area in 2017 (km^2)
Catchment 1	Soil moisture	N	Stung Chinit	Y	1771.3
Catchment 2	Soil moisture	N	Stung Chinit	Y	801.1
Catchment 3	Soil moisture	N	Stung Chinit	Y	769.2
Catchment 4	Soil moisture	N	Catch 4 River, Stung Chinit	Y	449.2
Catchment 5	Soil moisture	N	Stung Chinit	Y	412.5
Catchment 6	Soil moisture	N	Stung Chinit	Y	143.2
Catchment 7	Soil moisture	N	Stung Taing Krasaing	N	828.4
Catchment 8	Soil moisture	N	Catch 8 River, Stung Taing Krasaing	N	44.1
Catchment 9	Soil moisture	N	Stung Taing Krasaing	N	181.6
Catchment 10	Soil moisture	N	Catch 10 River, Downstream Floodplain	N	201.3
Catchment 11	Soil moisture	N	Catch 11 River, Downstream Floodplain	N	300.5
Catchment 12	Soil moisture	N	Downstream Floodplain	N	1627.5
Group 1	MABIA	Y	Chinit Main Canal	N	30.0
Group 2	MABIA	Y	Stung Taing Krasaing	N	76.6
Group 3	MABIA	Y	Stung Taing Krasaing Reservoir	N	12.1
Group 4	MABIA	Y	Chinit Main Canal	N	9.3
Group 5	MABIA	Y	Stung Chinit	N	16.4
Group 6	MABIA	Y	Chinit Main Canal	N	36.2
Group 7	MABIA	Y	Stung Taing Krasaing	N	4.5
Group 8	MABIA	Y	Catch 11 River, Downstream Floodplain	N	4.8

Table A2. Land use categories used in the Stung Chinit model, how they correlate with the WESTool land use categories and coverage of each land use type in 2002 and 2015.

WESTool Land Use Category	WEAP Land Use Category	2002 Area (km^2)	2015 Area (km^2)
Closed forest Open forest Wetland forest	Forest	4815	3259
Plantation	Plantation	2	203
Irrigated cropland Rainfed cropland	Non-Irrigated Rice [1]	1375	1722
Mosaic cropland	Mosaic Cropland	1281	2193
Pasture	Pasture	154	154
Urban	Urban	24	24
Water	Water	35	36
Wetland	Wetland	18	21
N/A	Irrigated Rice [1]	0	92

[1] The areas classified as Irrigated Rice, based on the explanation in the following section, are subtracted from the sum of area classified within the WESTool categories of Irrigated Cropland and Rainfed Cropland.

Table A3. Details of rice crop planting variations.

Crop Pattern	Rice (1)	Crop Name (1)	Plant Date (2)	Harvest Date (2)	Duration (1)	Water Depth (Assuming Plant by Transplant). Dry Season is Shaded. (3)	J	F	M	A	M	J	J	A	S	O	N	D
R1	Med	Pkar Rumdoul	June/July (4)	October/ November (4)	120 to 140 days	Plant						maint 3 cm						
						Grow							fill 20 cm	maint 20–30 cm				
						Harvest										dr		
R2	Early	IR 66	May	August	105 to 115 days	Plant					maint 3 cm							
						Grow						fill 20 cm	maint 20–30 cm					
						Harvest								dr				
	Med	Pkar Rumdoul	September	January	120 to 140 days	Plant									maint 3 cm			
						Grow										fill 20 cm	maint 20–30 cm	
						Harvest	dr											
R3	Early	IR 66	May	August	105 to 115 days	Plant					maint 3 cm							
						Grow						fill 20 cm	maint 20–30 cm					
						Harvest								dr				
	Early	IR 66	September	December	105 to 115 days	Plant									maint 3 cm			
						Grow									fill 20 cm	maint 20–30 cm		
						Harvest												dr
	Early	IR 66	January	May	105 to 115 days	Plant	maint 3 cm											
						Grow		fill 20 cm	maint 20–30 cm									
						Harvest				dr								

Table A3. *Cont.*

Crop Pattern	Rice (1)	Crop Name (1)	Plant Date (2)	Harvest Date (2)	Duration (1)	Water Depth (Assuming Plant by Transplant). Dry Season is Shaded. (3)												
							J	F	M	A	M	J	J	A	S	O	N	D
R4	Early	85 Day	May	July	85 days	Plant					maint 3 cm							
						Grow						fill 20 cm	maint 20–30 cm					
						Harvest							dr					
	Early	85 Day	August	October	85 days	Plant								maint 3 cm				
						Grow									fill 20 cm	maint 20–30 cm		
						Harvest										dr		
	Early	85 Day	November	January	85 days	Plant											maint 3 cm	
						Grow	(shaded)											fill 20 cm maint 20–30 cm
						Harvest	dr											
	Early	85 Day	February	April	85 days	Plant			maint 3 cm									
						Grow			fill 20 cm	maint 20–30 cm								
						Harvest				dr								

Med = Medium Variety, Early = Early Duration, dr = drain, maint = maintain. (1) Developed based on information from Ministry of Agriculture, Fishery and Forestry and Cambodian Agricultural Research and Development Institute. (2) Adapted from Irrigation Service Center (ISC) *Stung Chinit Watershed Rapid Assessment Report*; Sustainable Water Partnership, Winrock International: 2018. (3) International Rice Research Institute (n.d.). Step-by-Step Production http://www.knowledgebank.irri.org/step-by-step-production. (4) US Department of Agriculture. Cambodia: Future Growth Rate of Rice Production Uncertain; US Department of Agriculture: 2010. Available online: https://ipad.fas.usda.gov/highlights/2010/01/cambodia/ (accessed on 2 November 2020).

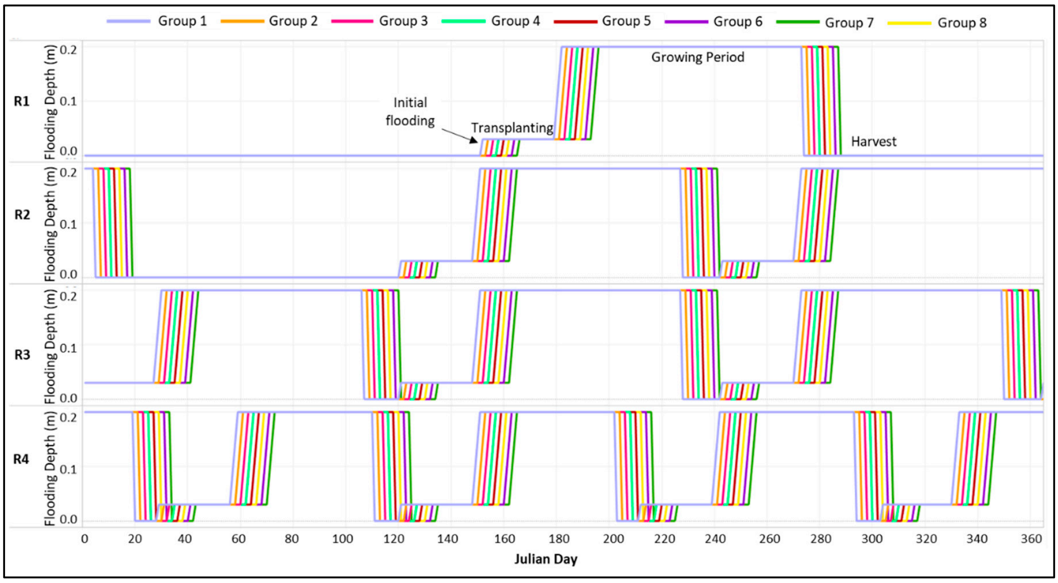

Figure A1. Rice irrigation schedule for four rice planting schedules in the 8 irrigation groups.

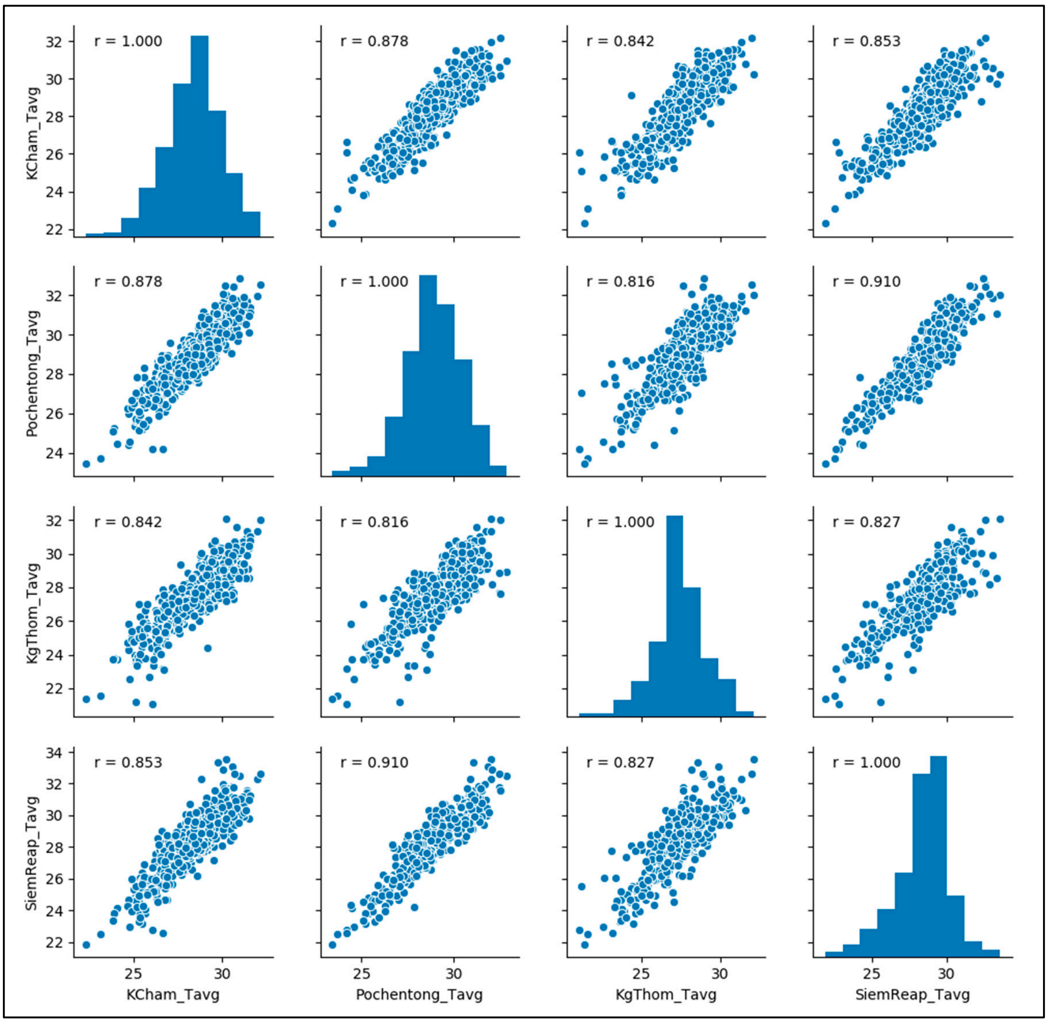

Figure A2. Comparison of weekly average temperature (°C) between each climate station with data (SiemReap, KgThom, Pochentong, KCham), for periods where data overlapped, and histograms of each station's data.

Table A4. Water source and use characteristics of village clusters.

Location of Villages	% Demand Sourced from Groundwater	% Demand Sourced from Surface Water	% Demand Sourced from Other Demand	Surface Water Source
Catchment 1	88	7	5	Stung Chinit
Catchment 2	83	17	0	Stung Chinit
Catchment 3	93	3	4	Stung Chinit
Catchment 4	95	3	2	Catch 4 River
Catchment 5	86	7	7	Stung Chinit
Catchment 6	97	2	1	Stung Chinit
Catchment 7	97	2	1	Stung Taing Krasaing
Catchment 8	87	4	10	Catch 8 River
Catchment 9	87	9	5	Stung Taing Krasaing
Catchment 10	91	4	4	Catch 10 River
Catchment 11	86	9	5	Catch 11 River
Catchment 12	92	7	1	Stung Chinit in downstream Floodplain

Table A5. Comparisons between WEAP outputs and values reported in other studies.

Variable	WEAP Simulation	Source 1	Source 2	Source 3
Reservoir evaporation	Range: 0.04–7.8 mm/day Average: 3.9 mm/day	4.5 mm/day [45]	4–5 mm/day [47]	Pan Evaporation Measurements: Range: 0.88–9.97 mm/day Average: 4.9 mm/day [58]
Deep percolation	Average: 0.25 mm/day	Range: 2–8 mm/day [46]		
Irrigation pre-saturation	250–300 mm (transplanting)	150–200 mm [45] (broadcasting)		
Wet season rice irrigation requirement	Average: 8433 m^3/ha	Average: 8000 m^3/ha [46]	Average: 7000 m^3/ha [45]	

Reservoir evaporation in the WEAP model is within the range of other estimated and measured evaporation values, though on the low end. Deep percolation calculated by WEAP is significantly lower than estimated by the reference study and should be adjusted in future work with more information about soil type and characteristics. WEAP's irrigation requirement for rice (both for pre-saturating fields and full season irrigation) is consistent with other studies. Pre-saturation requirements likely differ due to the different planting methods indicated, transplanting used in WEAP and broadcast used in the corresponding study's estimation.

References

1. UNDP Climate Change Country Profiles: Cambodia. Available online: https://www.geog.ox.ac.uk/research/climate/projects/undp-cp/UNDP_reports/Cambodia/Cambodia.hires.report.pdf (accessed on 3 November 2020).
2. International Food Policy Research Institute. *Building Climate Resilience in the Agriculture Sector of Asia and the Pacific*; Asian Development Bank: Manila, Philippines, 2009; ISBN 978-971-561-827-4.
3. Hasson, S.; Pascale, S.; Lucarini, V.; Böhner, J. Seasonal cycle of precipitation over major river basins in South and Southeast Asia: A review of the CMIP5 climate models data for present climate and future climate projections. *Atmos. Res.* **2016**, *180*, 42–63. [CrossRef]
4. Thoeun, H.C. Observed and projected changes in temperature and rainfall in Cambodia. *Weather Clim. Extrem.* **2015**, *7*, 61–71. [CrossRef]
5. Country Report of Cambodia Disaster Management. Available online: https://www.adrc.asia/countryreport/KHM/2013/KHM_CR2013B.pdf (accessed on 12 November 2020).
6. Bun, S.; Oeurng, C.; Lim, V.; Hornbuckle, J. Estimating Rice Water Use using Water Balance Approach: Case study in Cambodia. *Techo-Sci. Res. J.* **2014**, *2*, 17–24.

7. Keskinen, M.; Kakonen, M.; Tola, P.; Varis, O. The Tonle Sap Lake, Cambodia: Water-related conflicts with abundance of water. *EPSJ* **2007**, *2*. [CrossRef]
8. Agricultural Water Management Planning in Cambodia. Available online: http://www.iwmi.cgiar.org/Publications/issue_briefs/cambodia/issue_brief_01-awm_planning_in_cambodia.pdf (accessed on 12 November 2020).
9. Smith, D.; Hornbuckle, J. A review on rice productivity in Cambodia and water use measurement using direct and indirect methods on a dry season rice crop. *Tech. Rep. ACIAR* **2013**, *46*, 12.
10. Chhinh, N.; Millington, A. Drought monitoring for rice production in Cambodia. *Climate* **2015**, *3*, 792–811. [CrossRef]
11. Touch, V.; Martin, R.J.; Scott, F.; Cowie, A.; Liu, D.L. Climate change impacts on rainfed cropping production systems in the tropics and the case of smallholder farms in North-west Cambodia. *Environ. Dev. Sustain.* **2017**, *19*, 1631–1647. [CrossRef]
12. Cambodia Agricultural Research and Development. Available online: Institutehttps://www.cardi.org.kh/download.php?&file=Annual_Report_2012_Englsih.pdf (accessed on 12 October 2020).
13. Cambodia Halving Poverty by 2015–Poverty Assessment 2006. Available online: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/154931468214795356/cambodia-halving-poverty-by-2015-poverty-assessment-2006 (accessed on 12 October 2020).
14. Assessing the Economic Benefits of an Early Wet Season Rice Crop in Cambodia's Rainfed Lowlands. Available online: https://studylib.net/doc/7878276/assessing-the-economic-benefits-of-an-early-wet-season-ri (accessed on 2 November 2020).
15. US Department of Agriculture. *Cambodia: Future Growth Rate of Rice Production Uncertain*; US Department of Agriculture: Washington, DC, USA, 2010. Available online: https://ipad.fas.usda.gov/highlights/2010/01/cambodia/ (accessed on 2 November 2020).
16. Hunsberger, C.; Work, C.; Herre, R. Linking climate change strategies and land conflicts in Cambodia: Evidence from the Greater Aural region. *World Dev.* **2018**, *108*, 309–320. [CrossRef]
17. Nesbitt, H.J. *Rice production in Cambodia: Cambodia-Irrigation-Australia Project*; International Rice Research Institute: Manila, Philippines, 1997; ISBN 978-971-22-0100-4.
18. Kim, S. *Climate Change and Water Governance in Cambodia: Challenge and Perspectives for Water Security and Climate Change in Selected Catchments, Cambodia*; Sreymom, S., Sokhem, P., Eds.; Cambodia Development Resource Institute: Phnom Penh, Cambodia, 2015; ISBN 9789924500049.
19. Van Ty, T.; Sunada, K.; Ichikawa, Y.; Oishi, S. Evaluation of the state of water resources using Modified Water Poverty Index: A case study in the Srepok River basin, Vietnam-Cambodia. *Int. J. River Basin Manag.* **2010**, *8*, 305–317. [CrossRef]
20. Hecht, J.S.; Lacombe, G.; Arias, M.E.; Dang, T.D.; Piman, T. Hydropower dams of the Mekong River basin: A review of their hydrological impacts. *J. Hydrol.* **2019**, *568*, 285–300. [CrossRef]
21. Murphy, T.; Irvine, K.; Sampson, M. The stress of climate change on water management in Cambodia with a focus on rice production. *Clim. Dev.* **2013**, *5*, 77–92. [CrossRef]
22. Stewart, M.A.; Coclanis, P.A. *Environmental Change and Agricultural Sustainability in the Mekong Delta*; Springer: Dordrecht, The Netherlands, 2011; Volume 45, ISBN 978-94-007-0933-1.
23. Sithirith, M. Water governance in Cambodia: From centralized water governance to farmer water user community. *Resources* **2017**, *6*, 44. [CrossRef]
24. Chun, J.A.; Li, S.; Wang, Q.; Lee, W.-S.; Lee, E.-J.; Horstmann, N.; Park, H.; Veasna, T.; Vanndy, L.; Pros, K.; et al. Assessing rice productivity and adaptation strategies for Southeast Asia under climate change through multi-scale crop modeling. *Agric. Syst.* **2016**, *143*, 14–21. [CrossRef]
25. Thomas, T.; Ponlok, T.; Bansok, R.; De Lopez, T.; Chiang, C.; Phirun, N.; Chhun, C. Cambodian Agriculture: Adaptation to Climate Change Impact. *SSRN J.* **2013**. [CrossRef]
26. Shrestha, M.; Shrestha, S.; Datta, A. Assessment of climate change impact on water diversion from the Bago River to the Moeyingyi wetland, Myanmar. *Curr. Sci.* **2017**, *112*, 377. [CrossRef]
27. Shrestha, S.; Bhatta, B.; Shrestha, M.; Shrestha, P.K. Integrated assessment of the climate and landuse change impact on hydrology and water quality in the Songkhram River Basin, Thailand. *Sci. Total Environ.* **2018**, *643*, 1610–1622. [CrossRef] [PubMed]
28. Shrestha, S.; Shrestha, M.; Babel, M.S. Modelling the potential impacts of climate change on hydrology and water resources in the Indrawati River Basin, Nepal. *Environ. Earth Sci* **2016**, *75*, 280. [CrossRef]

29. Trang, N.T.T.; Shrestha, S.; Shrestha, M.; Datta, A.; Kawasaki, A. Evaluating the impacts of climate and land-use change on the hydrology and nutrient yield in a transboundary river basin: A case study in the 3S River Basin (Sekong, Sesan, and Srepok). *Sci. Total Environ.* **2017**, *576*, 586–598. [CrossRef]
30. Ministry of Environment Technical Coordination Unit for the Tonle Sap. *Tole Sap Ecosystem and Value*; 2001. Available online: http://www.mekonginfo.org/assets/midocs/0001325-environment-tonle-sap-ecosystem-and-value.pdf (accessed on 2 November 2020).
31. Teh, L.S.L.; Bond, N.; Kc, K.; Fraser, E.; Seng, R.; Sumaila, U.R. The economic impact of global change on fishing and non-fishing households in the Tonle Sap ecosystem, Pursat, Cambodia. *Fish. Res.* **2019**, *210*, 71–80. [CrossRef]
32. Sam, S.; Shinogi, Y. Performance assessment of farmer water user community: A case study in Stung Chinit irrigation system, Cambodia. *Paddy Water Environ.* **2015**, *13*, 19–27. [CrossRef]
33. Irrigation Service Center (ISC). Stung Chinit Watershed Rapid Assessment Report. In *Sustainable Water Partnership*; Winrock International: Krong Saen Monourom, Cambodia, 2018.
34. Yates, D.; Sieber, J.; Purkey, D.; Huber-Lee, A. WEAP21—A demand-, priority-, and preference-driven water planning model: Part 1: Model characteristics. *Water Int.* **2005**, *30*, 487–500. [CrossRef]
35. Winrock International. *Watershed Ecosystem Service Tool (WESTool)*; 2017. Available online: https://winrock.org/westool/ (accessed on 2 November 2020).
36. Sieber, J.; Purkey, D. WEAP: Water evaluation and planning system. In *User Guide for WEAP 2015*; Stockholm Environmental Institute (SEI): Stockholm, Sweden, 2015.
37. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration (Guidelines for Computing Crop Water Requirements)*; Food and Agriculture Organization of the United Nations: Rome, Italy, 1998; p. 326.
38. Sheffield, J.; Goteti, G.; Wood, E.F. Global meteorological forcing dataset for land surface modeling. *J. Climate.* **2006**, *19*, 3088–3111. [CrossRef]
39. International Water Management Institute (IWMI). *World Water & Climate Atlas*; 2002. Available online: https://www.iwmi.cgiar.org/resources/world-water-and-climate-atlas/ (accessed on 2 November 2020).
40. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013.
41. Shrestha, S.; Shrestha, M.; Babel, M.S. Assessment of climate change impact on water diversion strategies of Melamchi Water supply project in Nepal. *Appl. Clim.* **2017**, *128*, 311–323. [CrossRef]
42. Shrestha, M.; Acharya, S.C.; Shrestha, P.K. Bias correction of climate models for hydrological modelling—Are simple methods still useful? *Meteorol. Appl.* **2017**, *24*, 531–539. [CrossRef]
43. Asian Development Bank (ADB). *Cambodia: Stung Chinit Irrigation and Rural Infrastructure Project Completion Report*; Asian Development Bank: Manila, Philippines, 2009; p. 62.
44. International Centre for Environmental Management. The Impact of Water Supply Infrastructure on Floods and Droughts in the Mekong Region and the Implications for Food Production under the Mekong Challenge Program on Water and Food (MK12); Cambodia. 2014. Available online: https://icem.com.au/portfolio-items/the-impact-of-water-supply-infrastructure-on-floods-and-droughts-in-the-mekong-region/ (accessed on 3 October 2020).
45. Rousseau, P.; Balmisse, S.; Toelen, P.; Fontenelle, J.-P.; Castellanet, C. *Main Lessons Learnt from Project Implementation*; Groupe de Recherche et d'Echanges Technologiques (GRET), Cambodia Center for Study and Development in Agriculture (CDAC): Phnom Penh, Cambodia, 2009; Volume 26.
46. Lahmeyer IDP Consult, Inc.; TANCONS (Cambodia) co., Ltd. *Kingdom of Cambodia: Uplands Irrigation and Water Resources Management Sector Project Appendix 7: Subproject Feasibility Study: Taing Krasaing Irrigation System*; Asian Development Bank (ADB): Manila, Philippines, 2015.
47. Lahmeyer International; SMEC Cambodia Consulting Ltd. *Irrigation Infrastructure and Irrigation System Management Components; Stung Chinit Irrigation and Rural Infrastructure Project*; Ministry of Water Resources and Meteorology (MOWRAM): Phnom Penh, Cambodia; Asian Development Bank (ADB): Manila, Philippines, 2006.
48. Population Census 2008 (Province, District, Commune, Village Level). Available online: https://data.opendevelopmentcambodia.net/en/dataset/census-2008?type=dataset (accessed on 2 November 2020).

49. Forni, L.G.; Galaitsi, S.E.; Mehta, V.K.; Escobar, M.I.; Purkey, D.R.; Depsky, N.J.; Lima, N.A. Exploring scientific information for policy making under deep uncertainty. *Environ. Model. Softw.* **2016**, *86*, 232–247. [CrossRef]
50. Wopereis, M.C.S.; Kropff, M.J.; Maligaya, A.R.; Tuong, T.P. Drought-stress responses of two lowland rice cultivars to soil water status. *Field Crop. Res.* **1996**, *46*, 21–39. [CrossRef]
51. Fukai, S.; Ouk, M. Increased productivity of rainfed lowland rice cropping systems of the Mekong region. *Crop Pasture Sci.* **2012**, *63*, 944. [CrossRef]
52. Ikeda, H.; Kamoshita, A.; Yamagishi, J.; Ouk, M.; Lor, B. Assessment of management of direct seeded rice production under different water conditions in Cambodia. *Paddy Water Environ.* **2008**, *6*, 91–103. [CrossRef]
53. Tabbal, D.F.; Bouman, B.A.M.; Bhuiyan, S.I.; Sibayan, E.B.; Sattar, M.A. On-farm strategies for reducing water input in irrigated rice; case studies in the Philippines. *Agric. Water Manag.* **2002**, *56*, 93–112. [CrossRef]
54. Bouman, B.A.M.; Tuong, T.P. Field water management to save water and increase its productivity in irrigated lowland rice. *Agric. Water Manag.* **2001**, *49*, 11–30. [CrossRef]
55. System of Rice Intensification—SRI Information by Country. Available online: http://sri.ciifad.cornell.edu/countries/ (accessed on 5 October 2020).
56. Li, C.; Mosier, A.; Wassmann, R.; Cai, Z.; Zheng, X.; Huang, Y.; Tsuruta, H.; Boonjawat, J.; Lantin, R. Modeling greenhouse gas emissions from rice-based production systems: Sensitivity and upscaling. *Glob. Biogeochem. Cycles* **2004**, *18*. [CrossRef]
57. Shrestha, S.; Deb, P.; Bui, T.T.T. Adaptation strategies for rice cultivation under climate change in Central Vietnam. *Mitig Adapt. Strat. Glob. Chang.* **2016**, *21*, 15–37. [CrossRef]
58. Ministry of Water Resources and Meteorology (MOWRAM). *Rainfall Data from Phnom Penh Climate Station*; Ministry of Water Resources and Meteorology (MOWRAM): Phnom Penh, Cambodia, 2018.