Impact assessment of climate change on habitat suitability, Kikuchi river

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Impact assessment of climate change on habitat suitability, Kikuchi river

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Abstract

The continuous rate of warming observed in recent decades as a result of climate change is posing significant threats, especially on freshwaters ecosystems. Freshwaters are the most vulnerable part of an ecosystem to climate change which is supporting many species having limited ability to disperse in terms of changes in the environment, moreover; water temperature and availability are two dependent factors that are being affected by climate change. There is much evidence for climate change impacts on the hydro climatology of Japan. This country extends a large distance from north to south which makes hydrological processes affected by this phenomenon substantially. Therefore, as future alterations in climate are likely to cause substantial changes in the range of fish species by affecting hydrological and hydraulic parameters as well as the water temperature in the river, it would be so helpful to use projecting tool to visualize habitat suitability of fish species in the future.

The focus of the present dissertation is assessing the impact of climate change on habitat suitability of aquatic which are the first elements in a riverine ecosystem affected by this phenomenon. At present, few studies have been done for assessing climate change effects on fish habitat suitability especially by considering water temperature. In most of the studies simulating habitat suitability is based on hydraulic parameters including water depth and water temperature, however; one of this study's aims is simulations based on water temperature beside mentioned hydraulic factors and analyze which kind of parameters are affecting more habitat suitability.

The Kikuchi River located in the northern part of the Kumamoto Prefecture in Kyushu Island was selected as a study area. This river was chosen as its watershed is supporting 66 types of plants, 32 types of birds as well as 34 types of fish species. So, this watershed has a rich ecosystem especially by having important national parks. To do habitat suitability assessment, *Zacco platypus* (Oikawa) and *Zacco temminckii* (Kawamutsu) species were chosen as the target fish which are dominant in the Kikuchi river. These fish species are well-known as fish which are adapting to changes in habitat conditions easily. So, it is interesting to assess if they are also adaptive species to climate change especially changes in water temperature caused by this phenomenon.

In this regard, firstly two GCMs models including HadGEM2-ES and MICRO5 under two different RCPs (RCP4.5 and RCP8.5) were used to download future meteorological data (air temperature and precipitation). These data were downscaled with the LARS-WG method to be

usable for our study area scale. At the second step, the SWAT (Soil and Water Assessment Tool) model was used to simulate watershed hydrology in both baseline period (1986-2016) and future periods (2021-2040, 2041-2060 and 2061-208). As the next step, hydrological indicators and environmental components were analyzed by using IHA (Indicators of Hydrologic Alteration) software to assess how changes in meteorological parameters will affect flow regime (timing, frequency, duration, etc.) in the future. These changes will affect river wide and hydraulic parameters, therefore; by using iRIC (International River Interface Cooperative) software hydraulic simulations were done. This software was also used for habitat simulations in this study. Finally, WUA (Weighted Usable Area) was calculated with and without considering water temperature to find out which one of the hydraulic parameters or water temperature is affecting more habitat suitability of our target fish affected by climate change by 2080.

This study demonstrated that under HadGEM2-ES, annual rainfall is expected to increase about 70 (mm) and 50 (mm) in 2041-2060 and 2061-2080, however; under MICRO5 it is predicted to have a reduction for this meteorological parameter about 200 (mm) and 50 (mm) in 2041-2060 and 2061-2080, respectively. Both models showed average annual air temperature is expected to increase from 15.8 in the baseline period to 18.4 °C (RCP4.5) and 19.7 °C (RCP8.5) based on HadGEM2-ES, as well as; 17.9 °C (RCP4.5) and 19°C (RCP8.5) based on MOICRO5. As these changes will affect the flow regime it was important to work on changes in IHA and EFC to have the best evaluations on river flow in the future. The effects of these changes in meteorological parameters on hydrological indicators and environmental components were analyzed. Based on MICRO5 prediction under two RCPs, it is expected to have less river flow in the Kikuchi basin up to 6 (m^3/s) by 2080. This reduction has been also projected by HadGEM2-ES, except for two future periods including 2041-2060 and 2061-2080 in which streamflow will increase 2 (m^3/s) and 1 (m^3/s), respectively. This disagreement between these two models is because of having uncertainties in GCMs for Japan. Based on the IHA model output extreme events are expected to increase. For example, the frequency of extreme low flows and the count of high flow pulses are two parameters of EFCs which would be affected more by climate change in comparison with other indicators. For both parameters, it is expected to have a 60% increase within the next century. These changes will affect the river wide influencing on water depth and water velocity. The result showed that the highest and lowest levels of river flow are related to projections from HadGEM2-ES (RCP4.5) and MICRO5 (RCP8.5) in 2041-2060, respectively. By using the output of the SWAT model from these two GCMs, Nays2DH solver in iRIC software was run for three months including August, January, and July. Results showed, despite the water depth and velocity is decreasing in January and July, these hydraulic parameters will increase in August by 2060. It is expected to have more and stronger, floods having various side effects on ecosystem services as well as aquatic habitat suitability. Habitat suitability analyzes illustrated that as Oikawa fish prefer low water depth and water velocity, the month of August is not a suitable time for it in both adult and juvenile when the discharge of the river is in its average value. However, in the minimum value of river flow WUA in the Kikuchi river for Oikawa is about 4500 (m^2/Km) and 800 (m^2/km) which is expected to decrease in the future on August, as river discharge will increase even in its minimum value. At the average value of discharge, it is expected WUA will not change in January and July by 2060. This condition is the same for July at the minimum value of discharge, while; it is expected to decrease in January. This reduction mostly related to the decrease in the area having water. It means that in the future there will be some areas which used to have water but, in the future, they do not. So WUA will decrease, although HSI will increase for Oikawa fish. Based on our result habitat suitability of Kawamutsu fish is not the same for the adult and juvenile stage. It is expected to reduce in January at the average value of discharge in the adult stage, while; it will increase on the Juvenile stage. This is because of that in adult stage low water depth and velocity are not the fish preference but it is suitable at the juvenile stage. In August, WUA is expected to decrease and in January, HSI will increase at the minimum value of discharge by 2060, respectively. The month of July also does not have a suitable condition for Kawamutsu, except for juveniles at the minimum value of river flow which is supposed to have a slight increase in the future. The important point is that changes in the hydraulic parameter will not have a notable effect on WUA for Oikawa and Kawamutsu in comparison with the effects of this phenomenon when the water temperature is being considered. It means that WUA is expected to decrease from 4500 (m^2/km) to around 4400(m^2/km) on August, however; this reduction is from 3000(m^2/km) to about 2000 (m^2/km) (which is about 1000 (m^2/km)) when the impact of water temperature affected by climate change was analyzes. This reduction is happening for July as well so that it was expected not having any changes in WUA based on changes in hydraulic parameters while changes in water temperature will decrease WUA up to 60% for both target fish species.

Chapter 1: INTRODUCTION

1-1. Background

Changes in the mean and/or the variability of climate properties during decades or longer can be identified as Climate Change which may happen because of natural internal processes or external forcings such as volcanic eruptions, human activities (e.g. burning fossil fuels, changes in the composition of the atmosphere or land use), and modulations of the solar cycles (1). This phenomenon can be recognized by some symptoms such as increasing temperature trends, rising in sea level; losing ice mass in different parts of the world (2). In 1988, the Intergovernmental Panel on Climate Change (IPCC) was set up by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) which had following goals (3):

- To provide policymakers with regular assessments of the scientific basis of climate change,
- Assessing Climate Chang impacts and future risks,
- And recognizing options for adaptation

According to IPCC, by the end of the current century, the temperature is supposed to increase in the range of 1.1–6.4°C. On the other hand, changes in the trend of precipitation are also reported which is not similar in different parts of the world.

Significant changes in freshwater biological systems, hydrologic systems, and forestry and agriculture; related to this phenomenon, would be valuable to study in order to have a sustainable life in the future (4). In other words, assessing the impact of climate change on water resources is so vital since this part of the ecosystem is the first component that will be affected by this phenomenon as changes in temperature and precipitation patterns will change hydrological cycles (5,6).

Mkankam Kamga (2001) (7) studied the impacts of climate change on runoff in the Upper Benue River (Cameroon) using one of the Hadley Centre models. He illustrated that annual river flow ranges will change by -3% to +18%, due to increases in rainfall of up to 4 – 13% and in temperatures of 1–3°C. Various models are used to simulate watershed hydrology and runoff, including the SWAT (Soil and Water Assessment Tool) model. Rezaei Zaman et al. (2016) (8) and Lubini and Adamowski (2013) (9) studied climate change effects on water systems by using GCM (General Circulation Model) outputs to project future climate and investigated its effect on streamflow using the SWAT model. Rezaei Zaman et al. (2016) (8) showed that streamflow discharge in their case study dropped by up to 30% by the year 2099.

However, Lubini and Adamowski (2013) (9) reported that streamflow discharge in their case study rose by between 24_ 45% because of climate change effects. These results indicate that the effects of climate change on riverine ecosystems will vary from region to region. It is proven that in humid regions, such as Japan, increases in temperature will lead to an increase in the potential for heavy rainfall. In fact, the Japanese archipelago extends a large distance from north to south and contains temperate, subarctic, and subtropical climate zones where exposure to climate changes effects (5). Kudo et.a1 (2017) (5) studied on impact of climate change on agricultural water resources and they illustrated there is high uncertainty in GCMs for Japan especially in western Japan (particularly Chugoku, Shikoku, and Kyushu). Moreover, in terms of the 10-year drought discharge during the puddling stage, western Japan especially Kyushu showed an inconsistent trend with the distributions of the change. Discharge patterns influence on rivers and can affect the spatial and temporal availability of aquatic habitat. So that, increases in river discharge can enable connectivity to side-channels or decreases in river discharge can reduce the distribution of habitat types (10). So, it is important to project how climate change will affect habitat suitability in a watershed to have efficient watershed management. In the case of Kyushu island, it is more important as previous studies showed the complexity projecting in this part of the world.

Kikuchi river basin located in Kyushu Island which is an important river basin because of having national parks (Figure 1-1) and rich ecology. The river forms the foundation of the region's social, economic and cultural resources (11). This basin has 32 type birds, 66 type plants, 38 types of benthic animal and 34 type fish species such as salmon, eel, Ayu fish, Oikawa fish, and Kawamutsu fish.

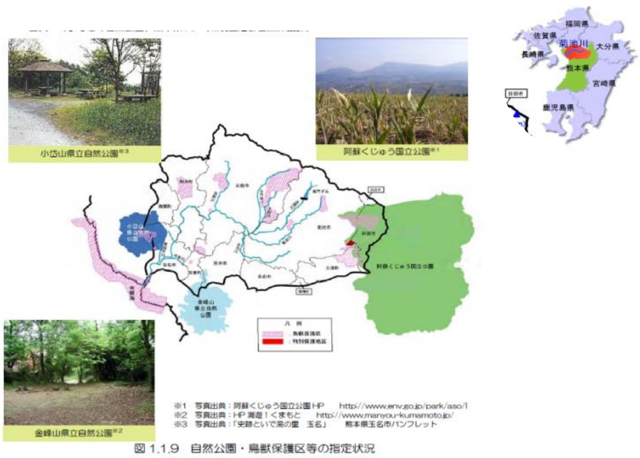

Figure 1-1 Kikuchi basin national parks(11)

Moreover, the Kikuchi basin is facing floods (Figure 1-2) frequently which is an extreme event happening there. Because it is surrounded by mountains on three sides of the area and the basin is near the center, rain falling on the upstream is easily gather on the ground (11).

a) b)

Figure 1-2 June 1984 flood: a) Yamaka City, b) Kikuchi City (11)

So it is important to assess the impact of climate change on habitat suitability in this case study to:

Make a vision of how will be fish species presence and abundance (10)

Have successful restoration strategies for saving biodiversity in the case study to maintain ecological flows (12).

Provide both a warning and an incentive for action in extreme conditions like floods (13).

In this study, habitat suitability of *Zacco platypus* (Oikawa) and *Zacco temminckii* (Kawamutsu) will be assessed (14). These two fish spices are dominant fish in the Kikuchi river and have been mentioned as indexes organisms for the evaluation of the countermeasures and the monitoring surveys (15). Generally, indicator, dominant, endangered, protected, sport, and commercial fish can be candidates for the target species. The target species should reflect the environmental constraints on the overall community and their abundance should be dependent on environmental changes that affect specific habitat variables (14) and these two target fish have required factors to study. There are many studies have been done on these spices some of which have been summarized in Table 1-1.

Table 1-1 Previous studies on habitat suitability

Authors		Nakagawa (2019) (16)	Choi & Choi (2018) (17)
Study aim		investigating the relationships between the population dynamics of fish species and changes in habitat characteristics	Impact of hydropeaking and thermopeaking on the downstream habitat using physical habitat simulation
Target fish		13 fish including *Zacco platypus*	*Zacco platypus*
Studied parameters	Water velocity	√	√
	Water Depth	√	√
	Sediment	√	-
	Substrate	√	√
	Water Temperature	—	(Ignoring Snowmelt, Groundwater, Average daily air temperature with a lag, Temperature of snowmelt runoff, Groundwater flow temperature) √
	Climate data	-	-
Achievements		Several fish species did not clearly decrease or increase at the sampling (*Zacco platypus)*	It was shown that the hydropeaking flows without the thermopeaking effect significantly decrease the WUA, except during the flood season.
Recommendations		The population dynamics of these species may have been driven by factors other than those examined in this study, for example, direct mortality from flood disturbances	Thermopeaking effect should be considered in the assessment of habitat suitability

Continue of Table 1-1

Authors		**YANAGAWA et al (2007) (15)**	**Kwon et al (2015)** (18)
Study aim		Improve the dam reservoir and downstream river environments	Predicting occurrence of endemic fish species with climatic and geographical variables using 6 SDMs
Target fish		Ayu and *Zacco platypus*	22 fish including *Zacco platypus*
Studied parameters	Water velocity	(No modeling) √	-
	Water Depth	(No modeling) √	-
	Sediment	(No modeling) √	-
	Substrate	-	-
	Water Temperature	(No modeling) √	-
	Climate data	-	√
Achievements		Flash discharge washes away attached algae on the riverbed	*Zacco platypus* have no changes in distribution by 2080
Recommendations		Continue to undertake long-term Environmental conservation measures	Considering water quality, micro-environmental factors and ecological factors

It is important to understand how climate change is affecting the discharge of the river, the physical parameter of the river such as depth and velocity, and water temperature. Studying these issues would be helpful to assess fish habitat suitability in the future to have better management of the watershed. As there are some gaps in previous studies for the habitat assessments, I am going to cover those gaps in our study. So that I will work on:

1) Long-term environmental conservation measures recommended by YANAGAWA et al (2007).

2) Hydraulic factors which are the gap of Kwon et al (2015) research.

3) habitat suitability in extreme events like flood periods which is Nakagawa (2019) recommendation

4) Improving water temperature modeling which is the gap of Choi & Choi (2018) in water temperature modeling

This study is following a multidisciplinary approach to assess impact of climate change on habitat suitability, so that; SWAT (Soil and Water Assessment Tool) as a hydrological model, Indicators of Hydrologic Alteration (IHA), and the International River Interface Cooperative (iRIC) software application provides an integrated river simulation environment, were used to assess habitat suitability of *Zacco platypus* and *Zacco temminckii*.

1-2. Problem statement and research questions

In this study, the impact of climate change on environmental flow components on habitat suitability in the Kikuchi River basin, which has important aquatic ecosystems and is a popular edible aquatic life resource, will be analyzed. So far, most of the studies of this basin have been focused on species living in the river. For example, Onikura et al., (2016) (19) studied how to protect bitterling species, by considering the impact of invasive species. Another study conducted in this basin was an impact assessment of low temperatures during the winter on local species, illustrating the importance of climate effects on aquatic life (20). So, as climate change is affecting hydrological and hydraulic river parameters as well as water temperature, it would be worthwhile to study this issue in this area. In this regards, the main key questions will be addressed through this study:

How will climate change affect water temperature and habitat suitability of the Kikuchi River?

Up to what extent target fish will be affected by climate change?

Which one of the hydraulic parameters or water temperature is affecting more habitat suitability of target fish?

Is the effect of climate change on the Kikuchi river negative only or there is any positive side effect of this phenomenon on our case study?

1-3. Research objectives

By identifying and understanding the climate change challenges, the main objectives of this study were designed as follows:

I. Providing an integrated study on impact assessment of climate change on habitat suitability.

II. Projecting the future climate in the case study based on general circulation models (GCMs).

I. Assessing the impact of climate change on hydrological (IHA) and environmental flow components (EFC).

V. Analyzing the effects of climate change on hydraulic parameters of the river and their impacts on fish habitat suitability.

1-4. Proposed approaches

The main objective of this study is the impact assessment of climate change on discharge in the Kikuchi River as well as its water temperatures. Therefore, 1) identifying and reducing the uncertainties introduced by different representative concentration pathways (here: RCP 4.5 and 8.5), different GCM (here: 2) for precipitation and temperature, 2) analyzing the impact of climate change of hydrological and environmental parameters, 3) projecting effects of this phenomenon hydraulic parameters of the river, and 4) analyzing habitat suitability and water temperature in the future periods are our basic goals. These analyses will be useful to know whether climate change will make the discharge of river increase or decrease and by any changes in this parameter, how other hydrological parameters as extreme flows will change. Moreover, assessing its climate change impact on water temperature in upstream and downstream will make us have better management on the river basin. Figure 1-3 presents the flowchart of this paper's methodology.

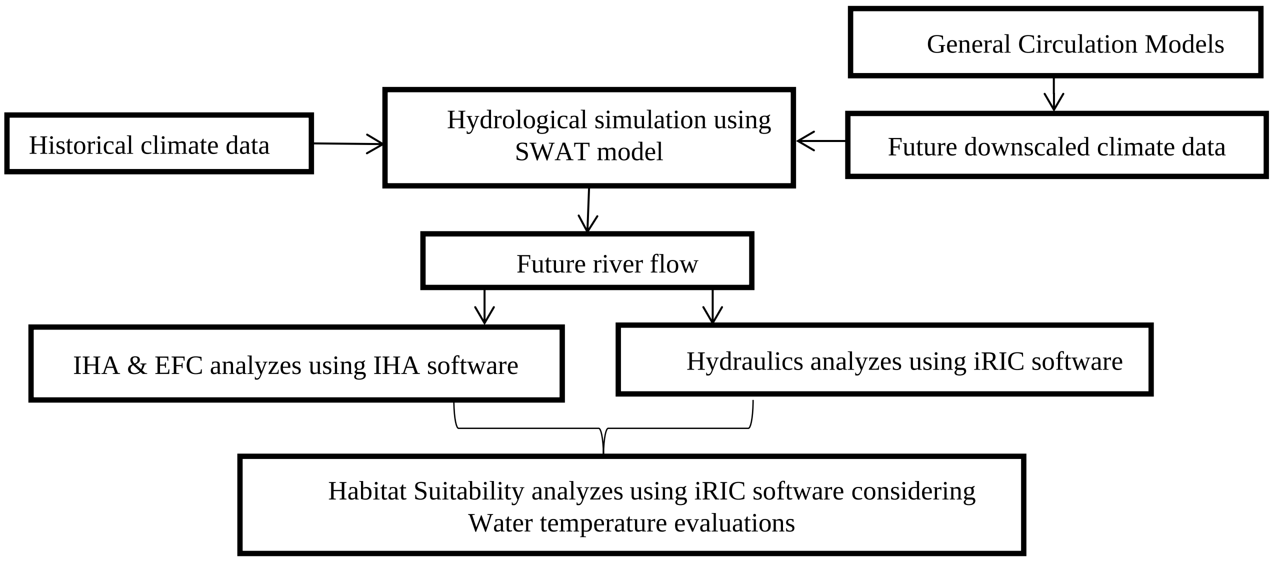

Figure 1-3. Flowchart of this study's methodology

1-5. Description of the study area

1-5-1. Study area

The Kikuchi River (菊池川, Kikuchi-gawa) (Figure 1-4) flows through the northern part of Kumamoto Prefecture in Kyushu Island, rises near Mt. Aso and flows west through the Kikuchi Valley. It turns south near Kikusui and empties into the Shimabara Bay. Kikuchi watershed lies within the confines 130°0'.20". –131°0' 49". E longitude and 32°51'44".—33°10' 8" N latitude having an area of 995 km² and the length of its longest branch is about 66 km (21). The Kikuchi River basin has an oval shape of approximately 45 km east to west and approximately 30 km north to south and the northern half of the basin is a mountain area with a steep mountain range of 700 to 800 m. The pyroclastic flow deposits are widely distributed in this area. Besides, offshore sediments near the coast are formed by land reclamation. Kikuchi River Basin has faced many floods during recent years so that the importance of river maintenance is known as a significant issue among hydrologists. Not only is this area important for human life but also it is serious for aquatic living including 34 fish species such as salmon, eel and Ayu fish (11).

The average annual precipitation in the case study is about 2134.5 mm and the average temperature is 15 C° (22).

Figure 1-4. Location map of the Kikuchi River basin

1-5-2. Case Study

- *Zacco platypus*

Zacco platypus (Figure 1-5), from the family of the pale chub, is a species of fish that is native to Japanese rivers and streams well-known as Oikawa in Japan. They can grow up to 20 centimeters, however; they usually grow up to 13 centimeters (23). Its diet consists of zooplankton and rivers that have a rapid flow are popular for adults. They do not really like stagnant and deep water (Figure 1-6). As their food source is located on the bottom, adults prefer living there. From May to August is their spawning period when they put eggs at the bottom of gravel with a diameter of 30-50 cm. After 4 days, larvae will be created whose length is about 7.2 mm but if they can be alive more and not to be hunted, their length would reach 14mm. in this time they prefer living in a water depth of 5-15 cm with slow water flow and be on the surface near the banks. At the juvenile stage, they have a strong tendency to go upstream where water depth is about 1 m (24).

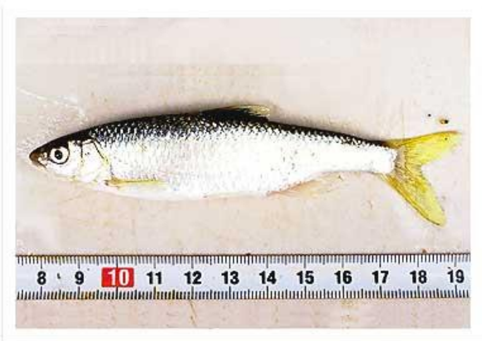

Figure 1-5 *Zacco platypus* (Oikawa) (25)

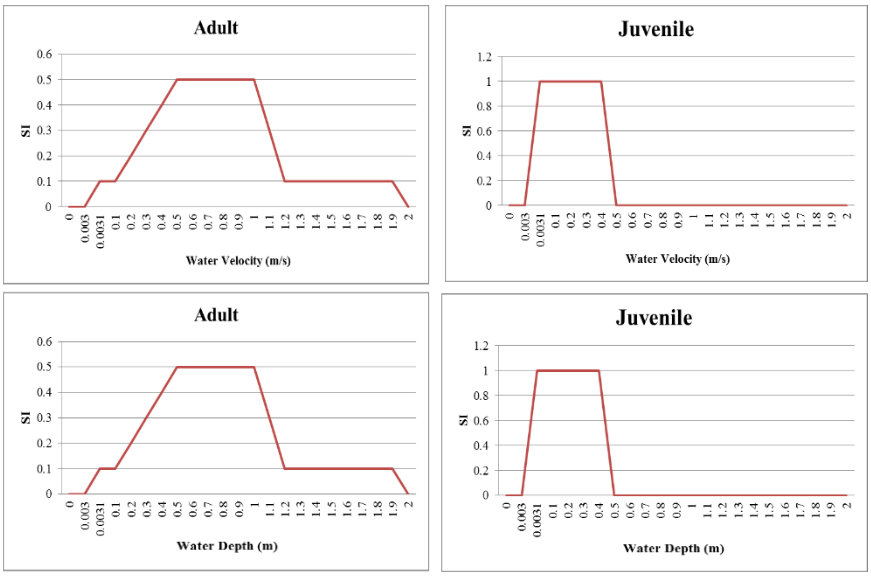

Figure 1-6 Oikawa habitat suitability curves (26)

- *Zacco temminckii*

Zacco temminckii (Kawamutsu) (Figure 1-7), is a subfamily of the Oikawa genus whose length is 15 cm living in the upstream and middle stream where the water velocity is low. The spawning season is May to August when they gather in a shallow area and lay eggs at the bottom covered by sands and gravels (24). Figure 1-8 shows the habitat suitability curve of this species.

Figure 1-7 *Zacco temminckii* (Kawamutsu)

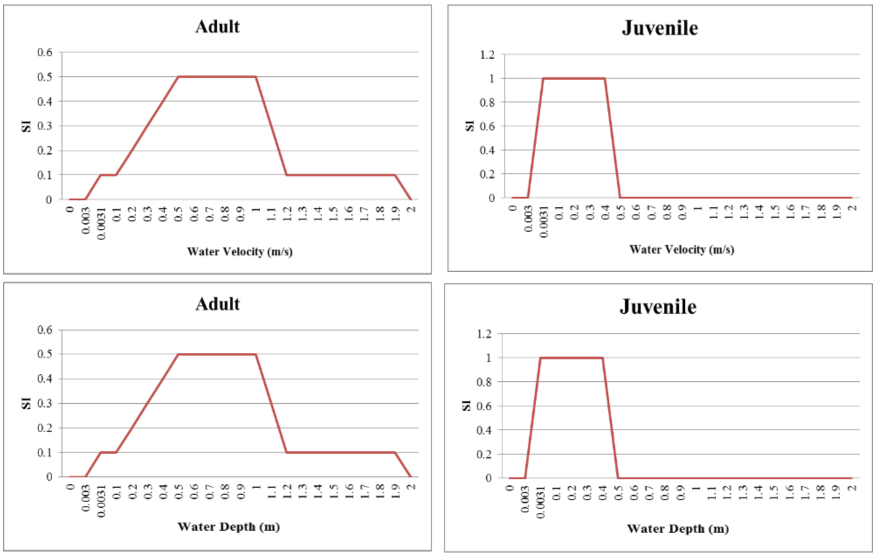

Figure 1-8 Kawamutsu habitat suitability curve (26)

Based on Choi and Choi (2018)(17) research, habitat suitability curve of water temperature for Oikawa is as Figure 1-9 which is considered same for Kawamutsu, as well.

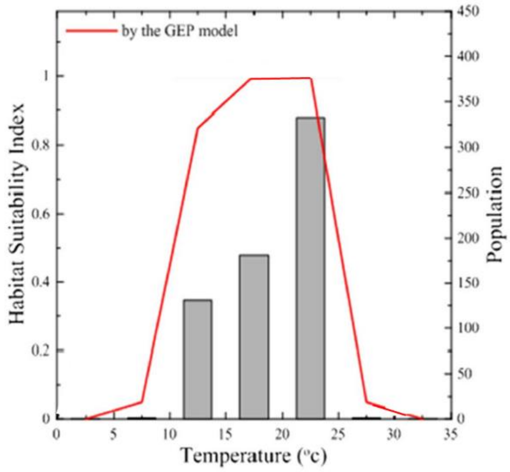

Figure 1-9 Water Temperature suitability curve (17)

1-6. Dissertation Structure

In this dissertation, research works were divided into six chapters. Each chapter will explain the detail results of research works that were carried out in this study. Briefly, introductions for each chapter are explained below:

Chapter 1: This chapter is an introduction of our work which highlighted the background of our research, problem statement, research questions, research objectives, proposed approaches, description of the study area, and dissertation structure.

Chapter 2: This chapter will discuss Climate Change and GCMs. Moreover, our projection of the Kikuchi River basin climate in the future periods will be explained here.

Chapter 3: This chapter will discuss river flow simulation by the SWAT model, river flow in the future, as well as; IHA and EFC changes in the future periods using IHA software.

Chapter 4: This chapter will discuss changes hydraulic river flow parameters in the future, by using Nays2DH solver developed in iRIC model.

Chapter 5: This chapter will discuss habitat suitability analyzed by EvaTrip solver in the iRIC model and water temperature simulated by the SWAT model.

Chapter 6: This chapter will conclude the research works and will have some recommendations for the improvement of current works.

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Chapter 2: Climate Change Models and Scenarios

2-1. Introduction

2-1-1. General Circulation Model

Climate change is one of the most significant challenges affecting all living matters on earth. This phenomenon can cause several hydrological and environmental problems related to water resources and ecological services (1). To assess climate change impacts and future risks, three-dimensional models, known as general circulation models (GCMs), can be used. In this regard, IPCC published AR5 and introduced the Coupled Model Intercomparison Project phase 5 (CMIP5). CMIP5 will notably provide a multi-model context to reach these three goals (2):

1) Evaluating the mechanisms responsible for model differences when there are poorly understood feedbacks related to the carbon cycle and with clouds,

2) Analyzing if the climate is predictable and understanding the ability of models to predict climate on decadal time scales, and, more generally,

3) Finding out the reason for the similarity of forced models producing a range of responses.

CMIP5 has prepared 40 GCMs some of which has mentioned in Table 2-1 (3). Table 2-1 Horizontal resolution (longitude × latitude in degree) of the 10 CMIP5 GCMs

	Model	Institution	Spatial resolution
1	BCC-CSM1.1	Beijing Climate Center (BCC), China	2.8125◦ × 2.8125◦
2	BNU-ESM	Beijing Normal University (BNU), China	2.8125◦ × 2.8125◦
3	CanESM2	Canadian Centre for Climate Modelling and Analysis,Canada	2.8125◦ × 2.8125◦
4	HadGEM2-AO	Met Office Hadley Centre, UK	1.875◦ × 1.2414◦
5	HadGEM2-ES	Met Office Hadley Centre, UK	1.875◦ × 1.2414◦
6	IPSL-CM5A-LR	Institute Pierre-Simon Laplace (IPSL), France	3.75◦ × 1.875◦
7	MIROC5	AORI, NIES, JAMSTEC, Japan	1.4063◦ × 1.4063◦
8	MIROC-ESM	AORI, NIES, JAMSTEC, Japan	2.8125◦ × 2.8125◦
9	MIROC-ESM-CHEM	AORI, NIES, JAMSTEC, Japan	2.8125◦ × 2.8125◦
10	MPI-ESM-MR	Max Planck Institute for Meteorology (MPI), Germany	1.875◦ × 1.875◦

A set of four new future scenarios, the so-called Representative Concentration Pathways (RCPs), was developed as a basis for the CMIP5 long-term and short-term modeling experiments (4). These future scenario simulations are continuations of the historical experiments, 1850–2005, and begin on 1 January 2006. The four RCPs reflect the range of year 2100 greenhouse gas radiative forcing values from 2.6 to 8.5 W/m2 (Figure 2-1): the lowest forcing level scenario RCP2.6 (5), two median range or stabilization scenarios RCP4.5 (6) and RCP6.0 (7), and the high-end or business as-usual scenario RCP8.5 (8).

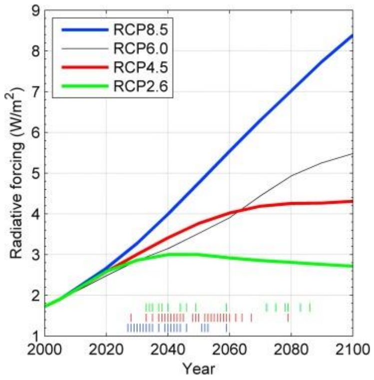

Figure 2-1 The four RCPs reflect the range of year 2100 greenhouse gas radiative forcing values (9)

2-1-2. Downscaling Method

The outputs provided by GCMs are too large to be useful in regional studies; therefore, downscaling of GCM outputs are usually employed to provide fine-resolution. There are different downscaling techniques that are based on statistical principles Weather generator and multiple regression are two most popular statistical methods which needless calculations for downscaling in comparison with other downscaling techniques (10).

A multiple regression model (called SDSM) is multiple regression-based tools for generating future scenarios to assess the impact of climate change having the ability to capture the inter-annual variability better than other statistical downscaling approaches. The other downscaling approach is the Long Ashton Research Station Weather Generator (LARS-WG) which is a weather generator technique. The LARS-WG can be used to synthesize daily data and fill in missing values of a recorded climatic time series. Based on Hashmi et al. (2011) study, both SDSM and LARS-WG models can be adopted with reasonable confidence as downscaling tools to assess the impact of climate change for the future (10).

For the Kikuchi watershed, the outputs of HadGEM2-ES and MICRO5 were used because they have a horizontal resolution of less than 1.8° in longitude and latitude (11) (Figure 2-2). In order to downscale GCMs models, the Long Ashton research station weather generator (LARS-WG) was used which has proven adequacy in simulating daily values and extreme events across diverse climates (12). The LARS-WG which is a statistical downscaling model to simulate weather data at a single site under current and future climate conditions based on the spell-length approach. Suitable climate variables used by this model are daily precipitation (in millimeter), maximum and minimum temperature (in Celsius), and solar radiation (13).

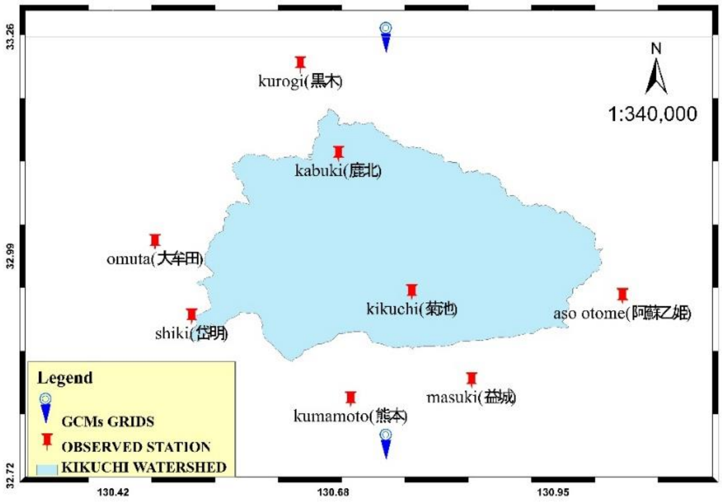

Figure 2-2 GCMs grids in Kikuchi watershed

2-2. Methods

2-2-1. Future climate projection

In this study, 1986 – 2016 was chosen as the baseline period, and 2021 – 2040, 2041 – 2060, and 2061 – 2080 are the periods analyzed for future climate. The software of LARSWG6 was used to downscale GCMs data, and the data of daily solar radiation was ignored. Moreover, CO2 concentration for the case study was considered as 410 ppm (14). LARS-WG is including calculations of the relevant statistical parameters for precipitation and temperature from the observed historical data. These parameters, as well as modified data, will be used for generating realistic climate data stochastically, corresponding to the present and future climate scenario, respectively (15). In this regard, daily maximum and minimum temperatures plus mean of observed daily precipitation at 8 stations (Table 2-2) located inside and outside of Kikuchi watershed for the period 1986–2016 were used to extract the statistical parameters of the current climate (Figure 2-3).

Table 2-2. Meteorological stations information(16)

ID	NAME	LATITUDE	LONDITUDE	ELEVATION	DURATION	PERCIPITATION (mm)
1	ASO OTOME	32.94	131.04	497	31(1986-2016)	2981.5
2	KABUKI	33.115	130.69	119	31(1986-2016)	2196.7
3	KIKUCHI	32.945	130.78	83	31(1986-2016)	1935.3
4	KUMAMOTO	32.813	130.7	37.7	31(1986-2016)	2024
5	KUROGI	33.225	130.645	144	31(1986-2016)	2047.9
6	MASUKI	32.84	130.85	193	14(2003-2016)	2173.6
7	OMUTA	33.01	130.47	40	31(1986-2016)	1924
8	SHIKI	32.91	130.52	15	31(1986-2016)	1793.1

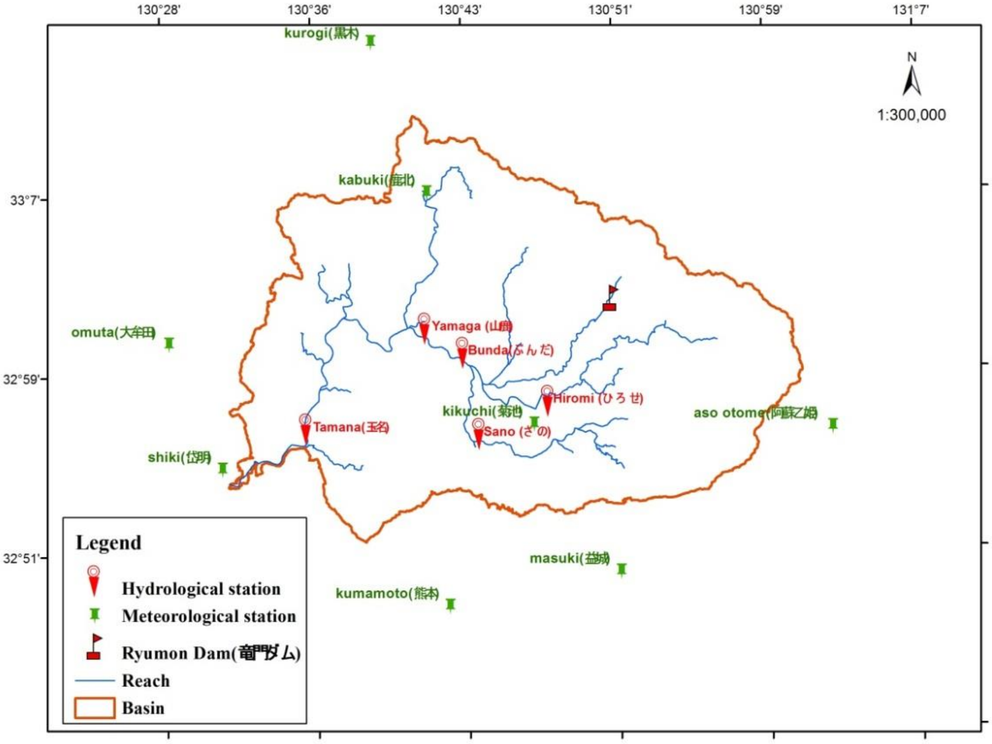

Figure 2-3 Meteorological and hydrological stations in Kikuchi watershed

2-3. Result and Discussion

2-3-1. Calibration and Validation LARS-WG Results

The Calibration and validation were carried out using the "Site Analysis" function in the LARS-WG model using data sets of observed station. The performance of the weather generator was checked using the Kolmogorov- Smirnov (K-S) test and T-test for all stations. In these tables for each site, the seasonal distributions of the wet and dry series were compared. The seasonal distributions correspond to the distributions for December–January–February

(DJF), March–April–May (MAM), June–July–August (JJA) and September– October–November (SON) (Table 2-3). The wet day is defined as the day with daily precipitation greater than or equal to 1 (mm/d). These performance checkings have been also done for Tmin and Tmax for months of the years in all eight stations (Table 2-4). Based on results from the K-S-test, the model performed very well in fitting the DJF (wet/dry), MAM (wet/dry), JJA (wet) and SON (dry) seasons for the datasets. Generally, LARS-WG is more capable of simulating the seasonal distributions of the wet/dry spells (17). The assessment results show that LARS-WG performance in simulating daily rainfall distributions for the Kikuchi, Kumamoto, and Masuki stations was perfect, however; in other stations, there are some months in which the model has poor performance such as Kabuki, Omuta, and Shiki, in December. This poor performance is due to a lack of data in some stations.

The simulation of both minimum and maximum temperature for observed data sets was perfect this is because of that weather generators generate synthetic weather time series which have statistical properties similar to the observed time series (17).

Table 2-3 KS-test for precipitation distribution for stations observed data

Seasonal wet/dry SERIES																									
		ASO OTOME			KABUKI			KIKUCHI			KUMAMOTO			KUROGI			MASUKI			OMUTA			SHIKI		
		KS-test	p-value	Assessment	KS-test	p-value	Assessment	KS-test	p-value	Assessment	KS-test	p-value	Assessment	KS-test	p-value	Assessment	KS-test	p-value	Assessment	KS-test	p-value	Assessment	KS-test	p-value	Assessment
DJF	wet	0.036	1	Perfect fit	0.074	1	Perfect fit	0.062	1	Perfect fit	0.068	1	Perfect fit	0.046	1	Perfect fit	0.022	1	Perfect fit	0.045	1	Perfect fit	0.021	1	Perfect fit
DJF	dry	0.082	1	Perfect fit	0.049	1	Perfect fit	0.034	1	Perfect fit	0.055	1	Perfect fit	0.034	1	Perfect fit	0.085	1	Perfect fit	0.049	1	Perfect fit	0.069	1	Perfect fit
MAM	wet	0.055	1	Perfect fit	0.052	1	Perfect fit	0.025	1	Perfect fit	0.045	1	Perfect fit	0.051	1	Perfect fit	0.027	1	Perfect fit	0.026	1	Perfect fit	0.073	1	Perfect fit
MAM	dry	0.086	1	Perfect fit	0.098	1	Perfect fit	0.069	1	Perfect fit	0.019	1	Perfect fit	0.053	1	Perfect fit	0.066	1	Perfect fit	0.083	1	Perfect fit	0.077	1	Perfect fit
JJA	wet	0.075	1	Perfect fit	0.05	1	Perfect fit	0.083	1	Perfect fit	0.055	1	Perfect fit	0.079	1	Perfect fit	0.058	1	Perfect fit	0.06	1	Perfect fit	0.081	1	Perfect fit
JJA	dry	0.112	0.997	very good fit	0.124	0.99	very good fit	0.095	1	Perfect fit	0.039	1	Perfect fit	0.064	1	Perfect fit	0.068	1	Perfect fit	0.11	0.998	very good fit	0.03	1	Perfect fit
SON	wet	0.031	1	Perfect fit	0.025	1	Perfect fit	0.035	1	Perfect fit	0.032	1	Perfect fit	0.061	1	Perfect fit	0.031	1	Perfect fit	0.046	1	Perfect fit	0.031	1	Perfect fit
SON	dry	0.081	1	Perfect fit	0.056	1	Perfect fit	0.089	1	Perfect fit	0.021	1	Perfect fit	0.054	1	Perfect fit	0.071	1	Perfect fit	0.037	1	Perfect fit	0.069	1	Perfect fit
Daily RAIN distributions																									
January		0.148	0.946	Perfect fit	0.175	0.837	Perfect fit	0.173	0.847	Perfect fit	0.086	1	Perfect fit	0.139	0.969	Perfect fit	0.096	1	Perfect fit	0.153	0.93	Perfect fit	0.203	0.679	Very good fit
February		0.087	1	Perfect fit	0.218	0.589	very good fit	0.115	0.996	Perfect fit	0.051	1	Perfect fit	0.241	0.459	Poor fit	0.092	1	Perfect fit	0.1	1	Perfect fit	0.121	0.993	Perfect fit
March		0.089	1	Perfect fit	0.14	0.966	Perfect fit	0.067	1	Perfect fit	0.127	0.987	Perfect fit	0.101	1	Perfect fit	0.08	1	Perfect fit	0.06	1	Perfect fit	0.127	0.987	Perfect fit
April		0.051	1	Perfect fit	0.082	1	Perfect fit	0.079	1	Perfect fit	0.145	0.954	Perfect fit	0.066	1	Perfect fit	0.179	0.816	Perfect fit	0.134	0.978	Perfect fit	0.069	1	Perfect fit
May		0.069	1	Perfect fit	0.162	0.897	Perfect fit	0.093	1	Perfect fit	0.113	0.997	Perfect fit	0.088	1	Perfect fit	0.091	1	Perfect fit	0.062	1	Perfect fit	0.207	0.655	Very good fit
June		0.095	1	Perfect fit	0.066	1	Perfect fit	0.219	0.584	very good fit	0.226	0.543	very good fit	0.055	1	Perfect fit	0.144	0.957	Perfect fit	0.248	0.423	Poor fit	0.129	0.985	Poor fit
July		0.315	0.165	Poor fit	0.062	1	Perfect fit	0.171	0.856	Perfect fit	0.078	1	Perfect fit	0.102	0.999	Perfect fit	0.189	0.761	Perfect fit	0.057	1	Perfect fit	0.098	1	Perfect fit
August		0.364	0.072	Poor fit	0.17	0.861	Perfect fit	0.15	0.94	Perfect fit	0.089	1	Perfect fit	0.167	0.875	Perfect fit	0.196	0.72	Perfect fit	0.178	0.821	Perfect fit	0.117	0.995	Perfect fit
September		0.1	1	Perfect fit	0.113	0.997	Perfect fit	0.053	1	Perfect fit	0.115	0.996	Perfect fit	0.234	0.497	Perfect fit	0.099	1	Perfect fit	0.131	0.982	Perfect fit	0.208	0.649	Very good fit
October		0.14	0.966	Perfect fit	0.13	0.984	Perfect fit	0.232	0.509	very good fit	0.131	0.982	Perfect fit	0.086	1	Perfect fit	0.117	0.995	Perfect fit	0.203	0.679	Very good fit	0.082	1	Perfect fit
November		0.18	0.811	Perfect fit	0.077	1	Perfect fit	0.095	1	Perfect fit	0.156	0.92	Perfect fit	0.17	0.861	Perfect fit	0.189	0.761	Perfect fit	0.197	0.714	Very good fit	0.129	0.985	Perfect fit
December		0.111	0.998	Perfect fit	0.25	0.412	poor fit	0.1	1	Perfect fit	0.18	0.811	Perfect fit	0.182	0.8	Perfect fit	0.158	0.913	Perfect fit	0.249	0.418	Poor fit	0.236	0.486	Poor fit

Table 2-4 KS-test for Tmin and Tmax distribution for stations observed data

Daily Tmin distribution																									
		ASO OTOME			KABUKI			KIKUCHI			KUMAMOTO			KUROGI			MASUKI			OMUTA			SHIKI		
		KS-test	p-value	Assessment	KS-test	p-value	Assessment	KS-test	p-value	Assessment	KS-test	p-value	Assessment	KS-test	p-value	Assessment	KS-test	p-value	Assessment	KS-test	p-value	Assessment	KS-test	p-value	Assessment
January		0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit
February		0.105	0.999	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit
March		0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit
April		0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit
May		0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit
June		0.085	1	Perfect fit	0.105	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.105	0.999	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit
July		0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.158	0.913	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit
August		0.053	1	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.105	0.999	Perfect fit	0.106	0.999	Perfect fit
September		0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.105	0.999	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.105	0.999	Perfect fit	0.106	0.999	Perfect fit
October		0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.085	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit
November		0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.105	0.999	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit
December		0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.105	0.999	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit
Daily Tmax distributions																									
January		0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.105	0.999	Perfect fit
February		0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.158	0.913	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit
March		0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit
April		0.053	1	Perfect fit	0.105	0.999	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit
May		0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.105	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit
June		0.053	1	Perfect fit	0.01	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit
July		0.105	0.999	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.158	0.913	Perfect fit	0.053	1	Perfect fit
August		0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.105	0.999	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit
September		0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.105	0.999	Perfect fit	0.105	0.999	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit
October		0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit
November		0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.053	1	Perfect fit
December		0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit	0.053	1	Perfect fit	0.106	0.999	Perfect fit	0.105	0.999	Perfect fit	0.106	0.999	Perfect fit	0.106	0.999	Perfect fit

In order to assess if the data generated by the weather generator comes from the same population as the observed ones, statistical tests are performed which is available in

Figure 2-4 illustrating the LARS-WG output of Kikuchi station for the baseline period. As a result, it was found out that there is a reliable agreement between observed and generated temperature data. However, about precipitation, there is a notable disagreement between HadGEM2-Es and MICRO5 outputs which roots in the uncertainty of GCMs in western Japan (11).

According to the predictions it is expected to have increased in precipitation under both scenarios of HadGEM2-ES during 2041-2060 and 2061-2080; while, a decrease in this variable is predicted for 2021-2040. It is notable that the result of the MOICRO5 model is different. Based on its results precipitation is expected to decrease under both RCPs for all three periods; though, under RCP8.5 there is an increase for the variable in 2061-2080 in comparison with previous periods. In terms of standard deviation for temperature, the LARS-WG has an average performance as it mostly underestimates the observed standard deviation, but it gives much better results for the precipitation (Figure 2-4).

2-3-2. Future Scenarios of Precipitation, Minimum and Maximum Temperature

Although, annual results of precipitation are mostly showing an increasing and a decreasing trend for HadGEM2-ES and MICRO5, respectively (Figure 2-5). Based on both these models it is expected to have a notable rise in June. The amount of rainfall this month for the baseline period is 450 mm and it is expected to grow to approximately 550 mm by 2080. Moreover, under both RCPs and both models, it is expected to have reductions from October to December (Figure 2-6).

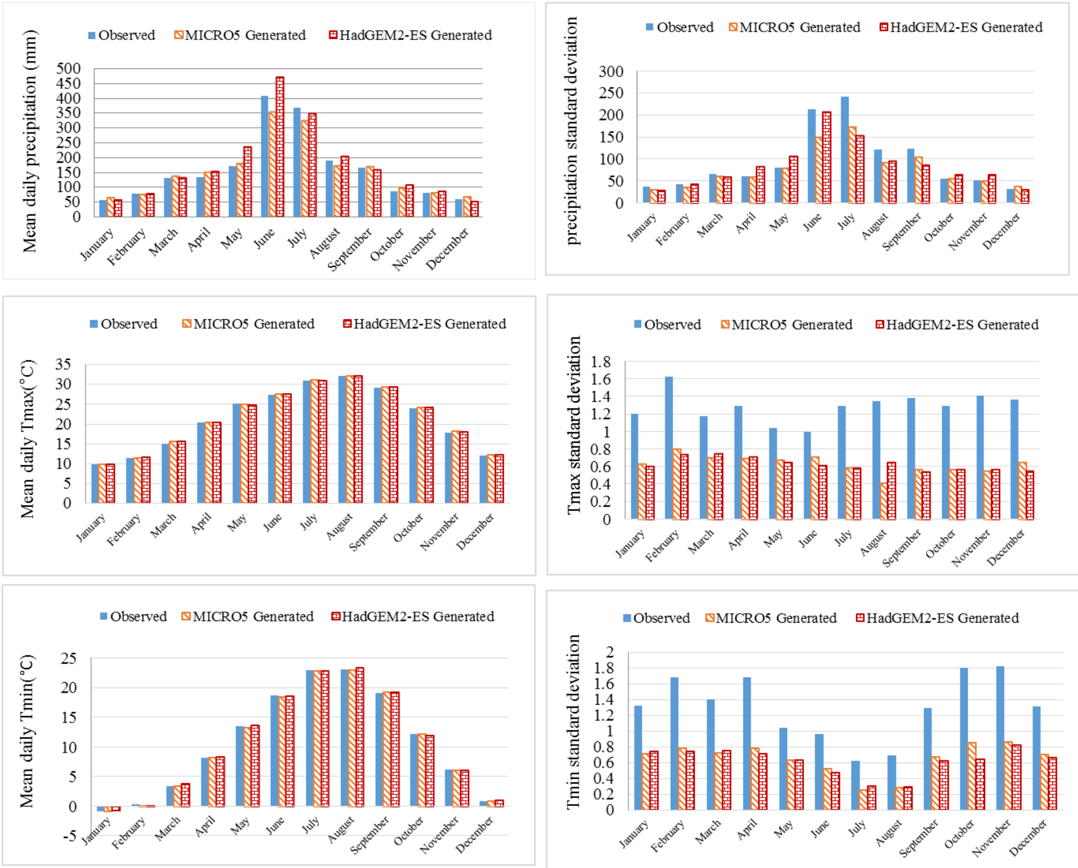

Figure 2-4. Comparison of observed and generated data with LARS-WG for precipitation, T_{max} and T_{min} at Kikuchi station (1986-2016)

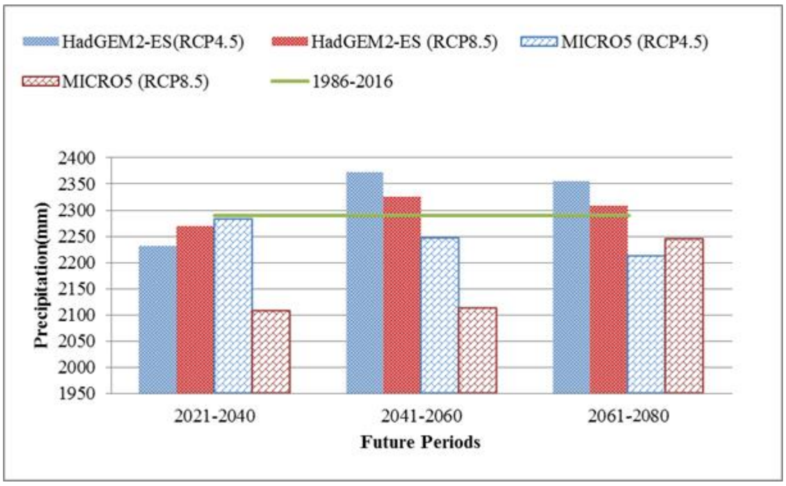

Figure 2-5. Predicted annual precipitation from GCMs models

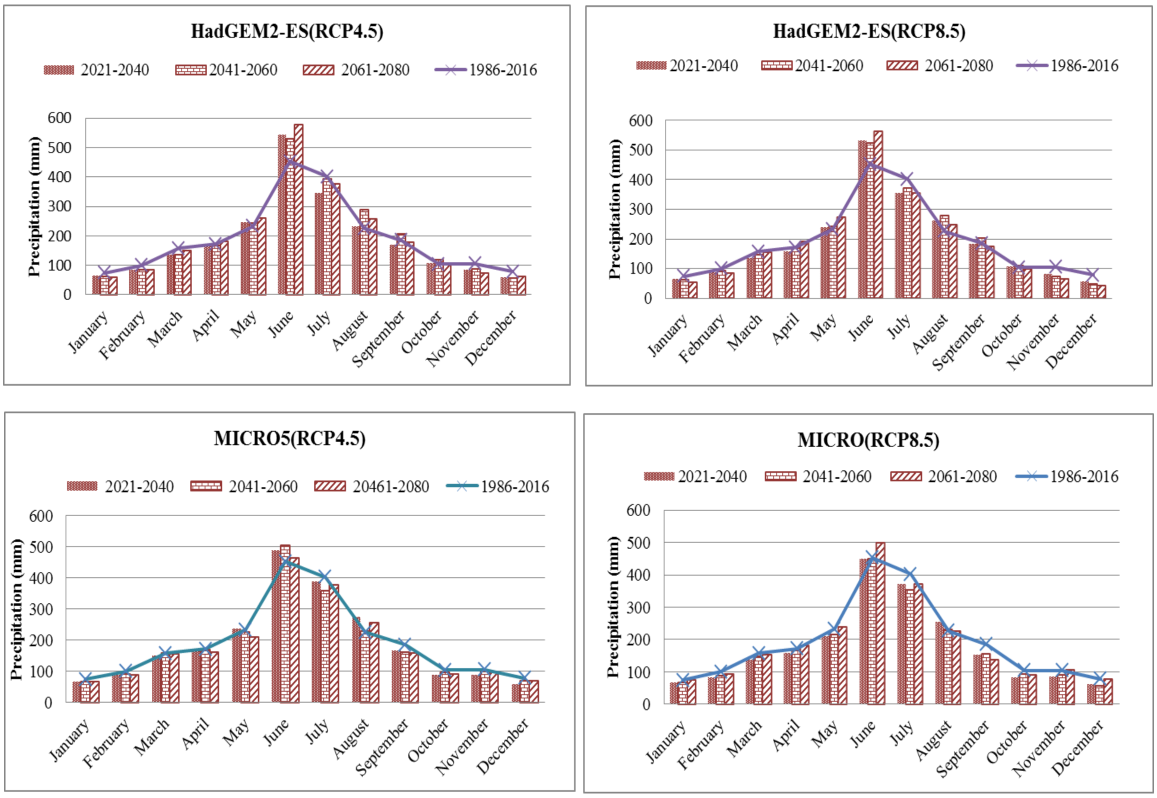

Figure 2-6. Predicted monthly precipitation from GCMs models

Both models showed average annual air temperature is expected to increase from 15.8 in baseline period (1986-2016) to 18.4 °C (RCP4.5) and 19.7 °C (RCP8.5) and 17.9 °C (RCP4.5) and 19°C (RCP8.5) based on HadGEM2-ES and MOICRO5, respectively. The same increasing pattern is predictable for average monthly temperature (Figure 2-7).

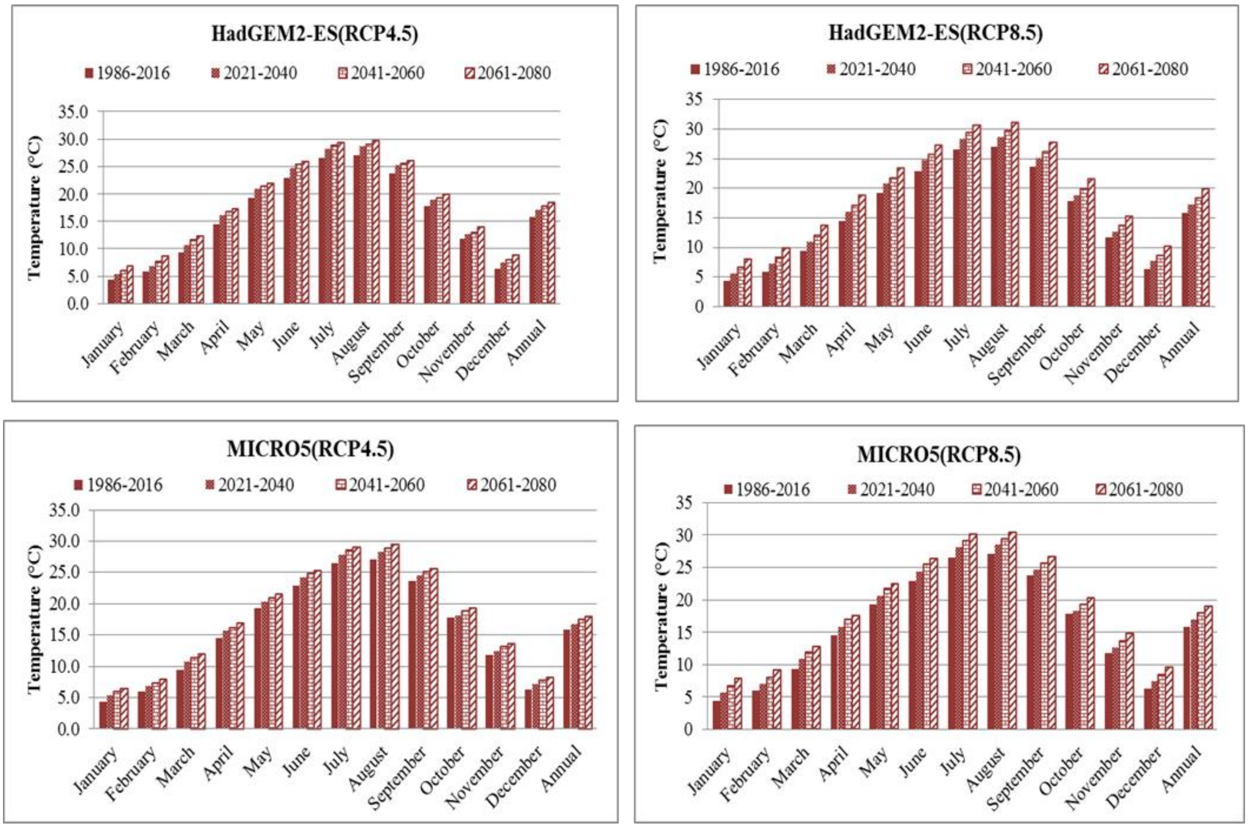

Figure 2-7. Predicted annually and monthly temperature

2-4. Conclusion

In this chapter, I assessed how climate change will affect the meteorological parameters in the Kikuchi river basin. In this regard, two different GCMs from CMIP5 were used including HadGEM2-ES and MICRO5 under two different RCPs (RCP4.5 and RCP8.5). The baseline period is 1986-2016 and the future periods are 2021-2040, 2041-2060, and 2061-2080.

As using GCMs is not possible directly, the LARS-WG downscaling method was used to downscale the GCMs data for our study area. The results showed different rainfall projections because of uncertainties in GCMs especially for Kyushu Island (11). In other words, except the projections for the first future period (2021-2040) in which there is an agreement about decreasing the precipitation under both used GCMs, for the other future periods, there are different predictions. It means, under HadGEM2-ES, annual rainfall is expected to increase about 70 (mm) and 50 (mm) in 2041-2060 and 2061-2080, respectively. However, under MICRO5 it is predicted to have a reduction for this meteorological parameter about 200 (mm) and 50 (mm) in 2041-2060 and 2061-2080, respectively. Both models showed average annual air temperature is expected to increase from 15.8 in the baseline period to 18.4 °C (RCP4.5) and 19.7 °C (RCP8.5), as well as; 17.9 °C (RCP4.5) and 19°C (RCP8.5) based on HadGEM2-ES and MOICRO5, respectively.

Changes in these climatic parameters are expected to affect the flow regime (18). In other words, the flow regime is regarded as a key driver of the river ecosystem function by many aquatic ecologists, which is being affected by climate change, directly. These functions are categorized into four main groups including timing, magnitude, frequency, and duration (19). Changes in these elements caused by climate change will make stress to riverine ecosystems (20). So, it is important to know how the results of our study about the impacts of climate change on meteorological parameters will affect hydrological functions of the Kikuchi river basin.

Therefore, in the next chapter, I will assess the impact of climate change on hydrological indicators and environmental components.

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Table of Contents

Chapter 3: Impact assessment of climate change on Hydrological Indicators and Environmental Flow Component

3-1. Introduction

Due to climate change, variations in the hydrological cycle will affect water resources especially rivers which are necessary parts of human civilization as well as environmental ecosystems (1,2). So that there are many studies have been done to analyze the impact of this phenomenon on hydrological indicators and environmental parameters. For example, Sarzaeim et al. (2017) (3) assessed the environmental water demand of the Karkheh River in Iran, under climate change by using the IHACRES model. Keeffe et .al (2018) (4) used the SWAT (Soil and Water Assessment Tool) model to project the impact of climate change on streamflow alteration affecting the spawning life stage of fish species. In this regard, the combined outputs of the SWAT model with IHA (Indicators of Hydrologic Alteration) software. Therefore, understanding the hydrological response of watersheds to climate change is important to cope with the possible effects of climate change on water resources management(5,6). IHA is being widely used, not only to assess climate change effects on environmental water demand (3) but also to analyze the Environmental Flow Components (EFC) of streamflow, which is important for managing flows during low flow periods and ecological functions during higher flows and floods. In other words, this parameter is mostly focusing on frequency, duration, timing, and the peak of hydrological factors such as flood, high/low-flow pulse, and extreme low flow which have direct and indirect effects of the ecosystem (7). This kind of combination is being used in other studies repeatedly such as Mittal et al. (2016) (8), Chatterjee et al. (2018) (9), Kiesel et al. (2019) (10) whose main goal is studying impact of climate change on flow alteration and predicting shifts in flood timing and magnitudes. These parameters will influence the ecological processes, and change aquatic ecosystems (8–10).

In this chapter, after simulating the Kikuchi River watershed using the SWAT model in the baseline period (1986-2016), river flow for future periods (2021-2040, 2041-2060, and 2061-2080) was projected. The future projection has been done by using downscaled outputs of HadGEM2-ES and MICRO5 models under two RCPs (RCP 4.5 and RCP 8.5). The outputs of the SWAT model were introduced to IHA to assess the impact of climate change on

Hydrological indicators and environmental flow components in the Kikuchi river. Soil and Water Assessment Tool (SWAT)

In this study, the SWAT model developed by the USDA (United States Department of Agriculture) was used to simulate streamflow.. This model is capable of assessing the impacts of climate change on water resources, and the simulation of the hydrologic cycle is based on the water balance equation (Figure 3-1) (11):

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})_i \qquad (3\text{-}1)$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_2O), Qsurf is the amount of surface runoff on day i (mm H_2O), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O), and Q_{gw} is amount of return flow on day i (mm H_2O).

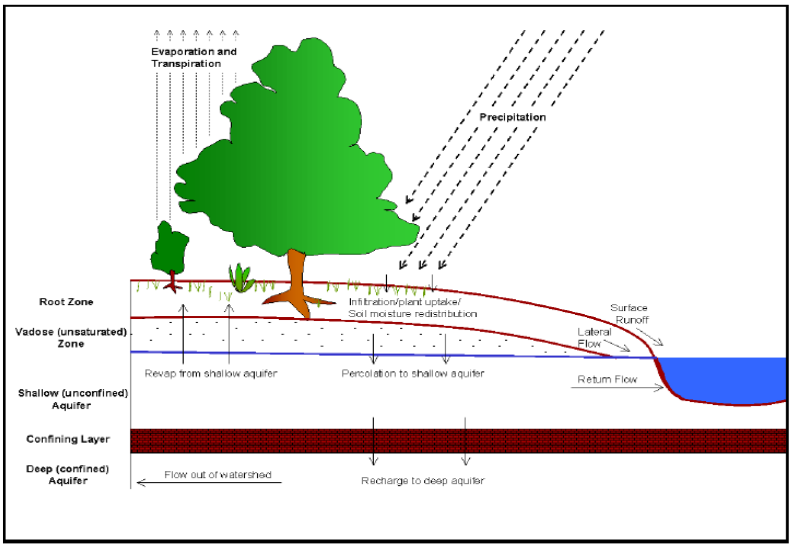

Figure 3-1. Considered hydrological components in SWAT model

3-1-1. IHA (Indicators of Hydrologic Alteration)

There are two general goals for hydrological assessment: 1) defining a series of hydrological attributes related to biological elements to characterizing inter-annual change; 2) making foundations for comparing hydrologic regimes before and after anthropological changes to a system. These goals would be achievable using an analysis of the inter-annual variation, as has been provided by IHA (12). This software calculates a total of 67 statistical parameters subdivided into two groups. The first group consists of the IHA parameters, which have been subdivided into five main groups, including: magnitude of monthly streamflows, duration and magnitude of annual extreme flows, frequency and duration of high and low pulses, timing of annual extreme flows, and rate and frequency of flow changes. The second group consists of the Environmental Flow Component (EFC) parameters, which are divided into five different types of parameters: low flows, high flow pulses, extreme low flows, small floods, and large floods. Changing these parameters would have certain environmental side effects which have been identified in the LLC et al. (13) study (Table 3-1).

Table 3-1. Brief information of IHA and EFC parameter in IHA software(13)

IHA Parameter Group	**Hydrologic Parameters**	**Ecosystem Influences**
1. Magnitude of monthly water conditions	• Mean or median value for each calendar month (12 parameters)	- Habitat availability for aquatic organisms - Influences on water temperature
2. Magnitude and duration of annual extreme water conditions	• Annual minimum and maximum for 1, 3, 7, 30, and 90 day means + number of zero-flow days + Base flow index (12 parameters)	- Structuring of river channel morphology and physical habitat conditions
3. Timing of annual extreme water conditions	• Julian date of each annual 1-day maximum and minimum (2 parameters)	- Access to special habitats during reproduction - Spawning cues for migratory fish
4. Frequency and duration of high and low pulses	• Number + Mean or median duration of high and low pulses (4 parameters)	- Availability of floodplain habitats for aquatic organisms
5. Rate and frequency of water condition changes	• Rise and fall rates + number of hydrologic reversals (3 parameters)	- Entrapment of organisms on islands, floodplains (rising levels)
	Grand total 33 parameters	
EFC Type	Hydrologic Parameters	Ecosystem Influences
1. Monthly low flows(10th percentile of average magnitude of monthly flow)	• Mean or median values of low flows during each calendar month (12 parameters)	- Provide adequate habitat for aquatic organisms
2. Extreme low flows (10th percentile of all low flows)	• Frequency, Duration (days),·Peak flow and Timing of extreme low flow (4 parameters)	- Enable recruitment of certain floodplain plant species
3. High flow pulses (return intervals of less than 2 years)	• Frequency, Duration (days),·Peak flow and Timing of extreme high flow + Rise and fall rates (6 parameters)	- Physical characteristics and shape of river channel, including pools and riffles
4. Small floods (return intervals of 2–5 years)	• Frequency, Duration (days),·Peak flow and Timing of small floods + Rise and fall rates (6 parameters)	- Provide migration and spawning cues for fish
5. Large floods (a 5 year return interval)	• Frequency, Duration (days),•Peak flow and Timing of Large floods + Rise and fall rates (6 parameters)	- Drive lateral movement of river channel, forming new habitats (secondary channels, oxbow lakes)
	Grand total 34 parameters	

This software is useful for planning ecosystem management activities, and also for setting and measuring progress toward restoration or conservation goals. It is notable that the thresholds for low and high flow pulses in the fourth IHA parameter group were defined as the

25th and 75th percentiles (IHA default), respectively, for the 30 year (1986 – 2016) period of daily natural flows simulated by the SWAT.

3-2. Materials

3-2-1. SWAT model

By using DEM, land use and soil shape files (Figure 3-2), plus precipitation and temperature data from observation stations (Table 2-2) for the baseline period, it is possible to calculate current river discharge.

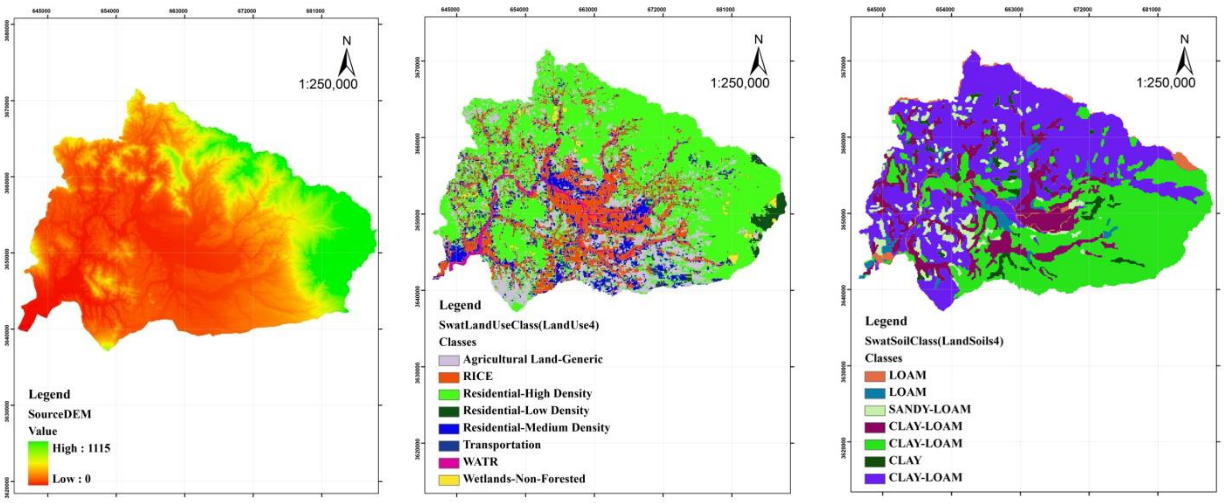

Figure 3-2. SWAT model input shape files

To calibrate and validate the SWAT model output, SWAT-CUP software was used. After that, future downscaled data was introduced to calibrated SWAT model as input to simulate future stream flow.

SWAT-CUP is a public domain program, and can be used as copied freely (14). The program links SUFI2, PSO, GLUE, ParaSol, and MCMC procedures to SWAT. It enables sensitivity analysis, calibration, validation, and uncertainty analysis of SWAT models. In this study SUFI2 was used in which parameter uncertainty accounts for all sources of uncertainties such as uncertainty in driving variables (e.g., rainfall), conceptual model, parameters, and measured data. There are five hydrological stations (Table 3-2) with which calibration and validation processes have been done.

Table 3-2 Hydrological station on the Kikuchi River(15)

ID	NAME	LATITUDE	LONGITUDE	DURATION	Q(m^3/s)
1	Hiromi (ひ ろ せ)	32.95	130.79	30(1986-2015)	9.02
2	Sano (さ の)	32.93	130.73	29(1986-2015)	3.97
3	Bunda (ぶ ん だ)	32.99	130.72	30(1986-2015)	26.68
4	Tamana (たまな)	32.99	130.58	26(1986-2012)	37.5
5	Yamaga(や ま が)	33.01	130.69	26 (1990-2015)	39.4

3-2-2. IHA model

- ***IHA groups***

Based on Fitzhugh (2014) study, the definition of IHA groups are as bellow (7):

Group 1) the magnitude of the water condition is a measure of the suitability or availability of habitat and wetted area or habitat volume, or the position of a water table.

Group 2) the magnitude and duration of annual extreme condition such as floods or droughts during certain cycles including the 1-day, 3-day, 7-day (weekly), 30-day (monthly), and 90-day (seasonal) extremes which are useful to understand environmental stresses and disturbances during the year.

Group 3) to determine whether certain life-cycle requirements are met or can influence the degree of stress or mortality associated with extreme water conditions such as floods or droughts, the timing of occurrence of particular water conditions can be analyzed.

Group 4) in this group, frequency (the number of annual occurrences) and duration of the water condition exceeds an upper threshold or remains below a lower threshold during a year were analyzed.

Group 5) the number and mean rate of both negative and positive changes in water conditions from one day to the next, were analyzed in this group. This parameter can give us enough information about the suddenness and number of internal cycles of environmental variation.

- ***EFC groups***

Group 1) in this group Low flows above 10th percentile of average magnitude of monthly flow and changes in this group affects maintenance of water temperatures suitability as well as dissolved oxygen, moreover; first group of IHA parameter is also causing this same side effect intensifying vulnerability of aquatic habitat suitability (7,13).

Group 2) 10th percentile of all low flows is known as extreme low flows analyzed in this group (7,13).

Group 3) high-flow pulses are flows which have return intervals of less than 2 years affecting physical shape of river channel. Moreover, the size of streambed substrates (sand, gravel, cobble) would change during this 100 years which is one of most important variables for aquatic habitat suitability (13,16).

Group 4) small floods are events with return intervals of 2–5 years whose raise influencing fish spawning in floodplain as well as providing new feeding opportunities would be affected by climate change (7,13).

Group 5) in this group large floods were analyzed which are events that have peaks corresponding to a 5 year return interval event or greater. river structure and physical shape would change and also organism materials (food) would be brought out of channel by changes in this group (7).

3-3. Results and Discussion

3-3-1. Impacts of climate change on discharge of the Kikuchi River

A Sequential Uncertainty Fitting (SUFI2) algorithm (17) was used in this study to calibrate and validate the SWAT model, using available monthly data of streamflow for Kikuchi river stations. Calibration of the models was carried out using data from 1986 – 2010, while model validation was performed by comparing simulated and measured stream flow data from 2010 to 2015. The SWAT model uses several parameters to simulate river discharge, so the most effective parameters were selected based on the results of a sensitivity analysis. The calibration parameters for the hydrological simulation and their best values following calibration are shown in Table 3-3.

Table 3-3 Best estimates for parameters in the calibration process

Parameter_Name	Fitted_Value	Parameter_Name	Fitted_Value
1. CN2mgt (Initial SCS runoff curve number for moisture condition II)	81.4	11. CH_K2. rte (Effective hydraulic conductivity in main channel alluvium (mm/hr))	195.0
2. ALPHA_ BF.gw (Alpha factor for ground water recession curve of the deep aquifer (1/days))	0.4	12. ALPHA_BNK.ret (Below alpha factor for bank storage (days))	0.3
3. GW_ DELAY.gw (Ground water delay time)	336.3	13. SOL_K (Standard hydraulic conductivity(mm/hr))	7.0
4. GWQMN. gw (Threshold depth of water in the shallow aquifer required for return flow to occur (mm H2O))	713.0	14. SOL_AWC (Available water capacity of the soil layer (mm H2O/mm soil)	0.3
5. PLAPS. sub (Precipitation lapse rate (mm H2O/km))	1.5	15. GW_REVAP. gw (Groundwater ‘‘revap’’ coefficient)	0.0
6. SMFMX. bsn (Melt factor for snow on June 21 (mm H2O/8C-day)	11.9	16. SOL_Z.sol (Depth from soil surface to bottom of layer (mm)	22.9
7. SMFMN. bsn (Melt factor for snow on December 21 (mm H2O/8C-day))	11.6	18. SOL_EC.sol (Electrical conductivity (dS/m))	98.8
8. EPCO. hru (Plant uptake compensation factor)	0.9		
9. RCHRG_DP.gw (Deep aquifer percolation fraction)	0.5	19. SHALLST. gw (Initial depth of water in the shallow aquifer (mm H2O))	90.5
10. OV_N. hru (Manning’s ‘‘n’’ value for overland flow)	2.7		

Figure 3-3 shows simulated and measured monthly streamflows for the calibration and validation periods. Three indicators including, R2 (the coefficient of determination), Nash–Sutcliffe Efficiency (NS) and Percent bias (PBIAS), are analyzed to test the validity of calibration. NS>0.5 and R2>0.5 are acceptable for streamflow simulation. Moreover, PBIAS < ±10 and ±10 < PBIAS <±15 is considered as a very good and good performance of the model, respectively (18,19). In this study, the SWAT model has a satisfactory performance concerning river flow simulation (Table 3-4).

Table 3-4. SWAT model calibration and validation performance

	R2	NS	PBIAS
Calibration(1986-2010)	0.91	0.89	-14.6
Validation(2011-2015)	0.95	0.93	-4.9

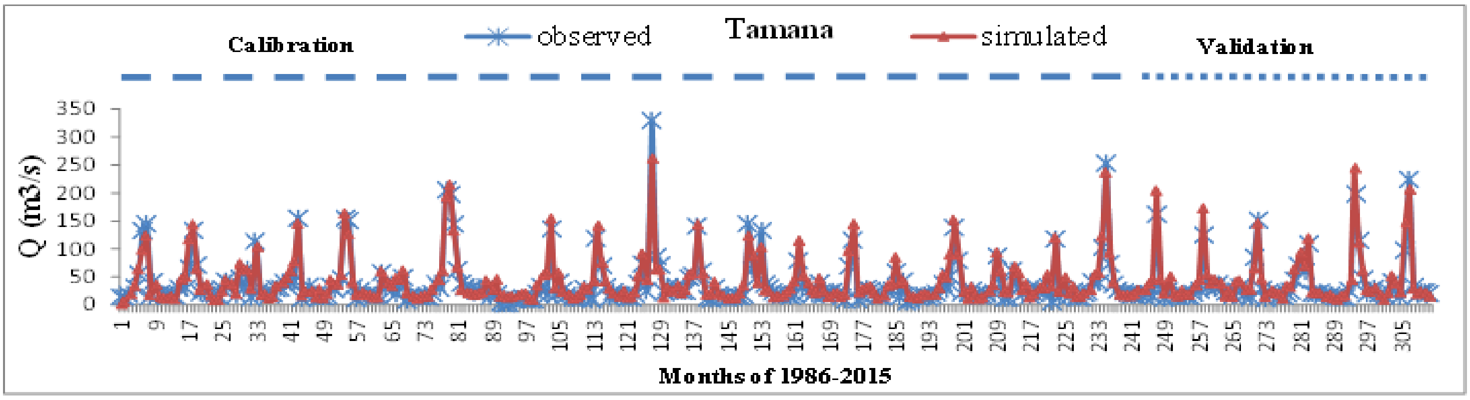

Figure 3-3 Observed and simulated discharge for Kikuchi River

The effects of climate change on hydrological variables in the future were evaluated based on the outputs from a baseline period (1986 – 2016). As a general view, results illustrated that the annual discharge of Kikuchi basin will decrease from 46m^3/s to approximately 43m^3/s, however; HadGEM2-ES showed it can be expected to have an increase in streamflow up to 47 m^3/s (RCP8.5) by 2080. The most reductions and rises in discharge of river are predicted by MICRO5 under RCP8.5 (41m^3/s) and HadGEM2-ES under RCP4.5 (48 m^3/s) on 2041-2060, respectively (Figure 3-4).

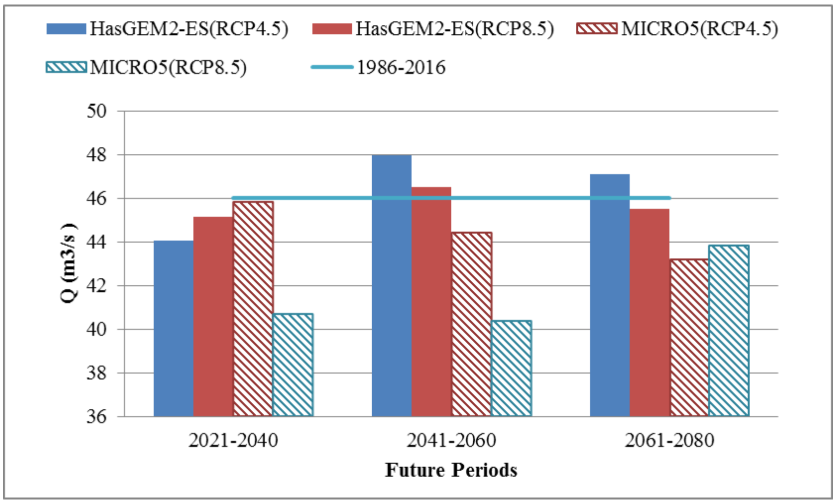

Figure 3-4. Simulated annual streamflow from SWAT model

To have a better vision about changes in extreme events in the future, Flow Duration Curve (FDC) was prepared (Figure 3-5). FDC represents the percentages of time flow happened in the river (Q10, Q20, Q30, etc.). The flow corresponding to Q90 should be the minimum flow available for drinking water or irrigation projects. The average flow, i.e., 50% of time flow at the Kikuchi river outlet is 14 (m^3/s) which is predicted to be same for the future. The low flow, Q90 which represents the base flow is 3 (m^3/s), projected to have 1 (m^3/s) decrease by 2080.

The maximum discharge observed is 113(m^3/s), which will increase to 130 (m^3/s) under HadGEM2-ES (RCP4.5) and decease up to 100 (m^3/s) under MiICRO5 (RCP 8.5). This information is useful to estimate the design flood.

In addition, under all RCPs of both models it is expected to have reductions from January to May, however; from June to December stream flow is expected to rise. These decreasing and increasing are more feasible under RCP8.5 of MICRO5 and RCP4.5 under HadGEm2-ES, respectively (Figure 3-6).

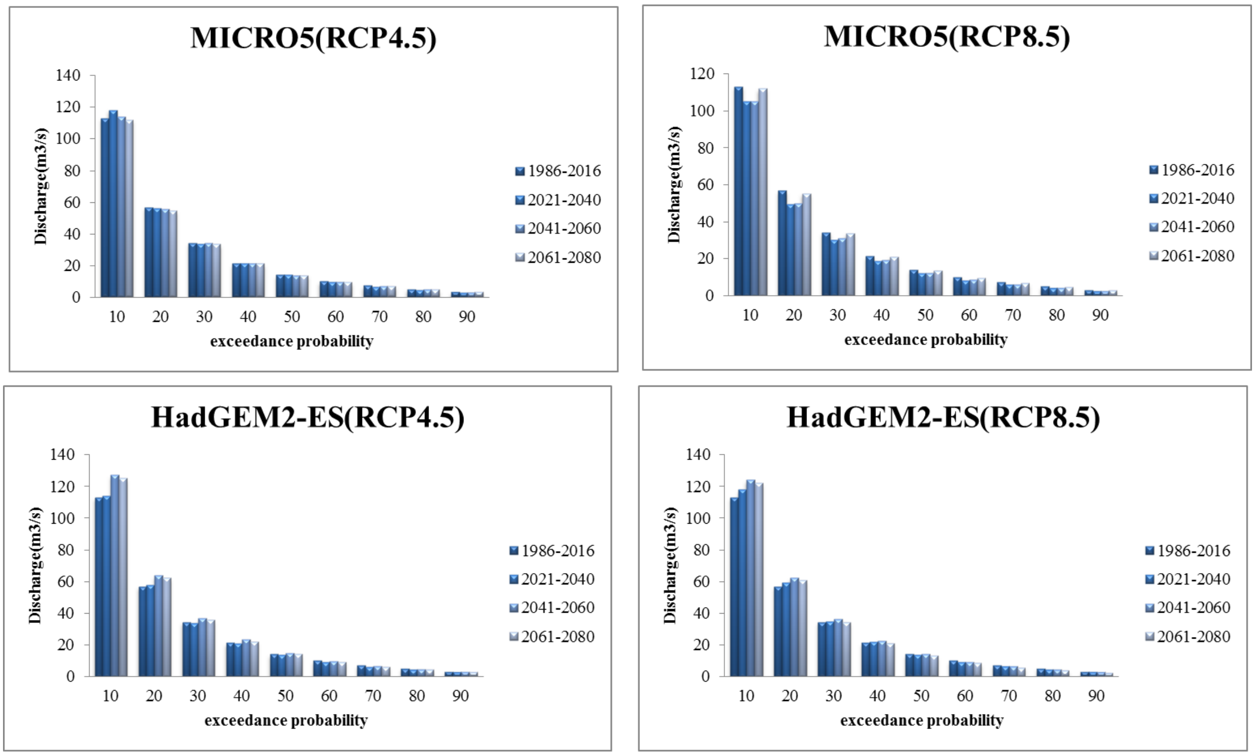

Figure 3-5 Flow Duration Curve for Kikuchi basin

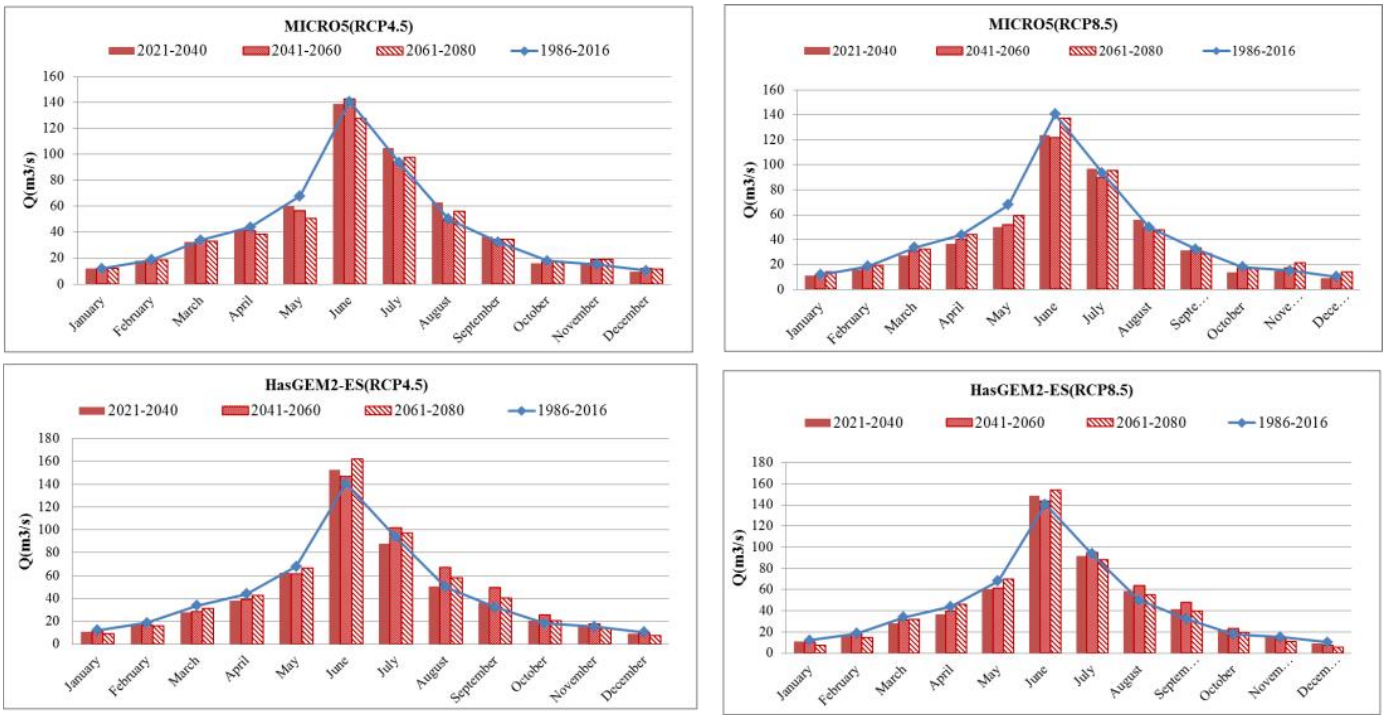

Figure 3-6. Simulated monthly streamflow from SWAT model

3-3-2. Impacts of climate change on hydrological indicators and environmental components

After carrying out calibration and validation for the SWAT model, the future discharge of the river was simulated using future precipitation and temperature data. According to scenarios, monthly averages of discharge in the Kikuchi River decreases, however; the frequency of high flow pulses (when water levels rise above the 75th percentile of pre impact daily flows (12)) will increase by 2080 (Figure 3-7). Moreover, results show that peaks of high flow pulses are expected rise from maximum 180 m^3/s in baseline period up to 200m^3/s (Figure 3-8). To have a better overview of climate change impacts on EFC as well as IHA parameters, the percentages of changed values of 34 indicators among their groups have been estimated. The frequency and peak of extreme low flows (the lowest 10% of initial low flow days (7)), frequency of small and large floods as well was duration of this parameter are affected more by climate change so that changes in these parameters are more than 50% increases. On the other hand, the peak of small floods will decrease more than 30% by climate change effects (Figure 3-9).

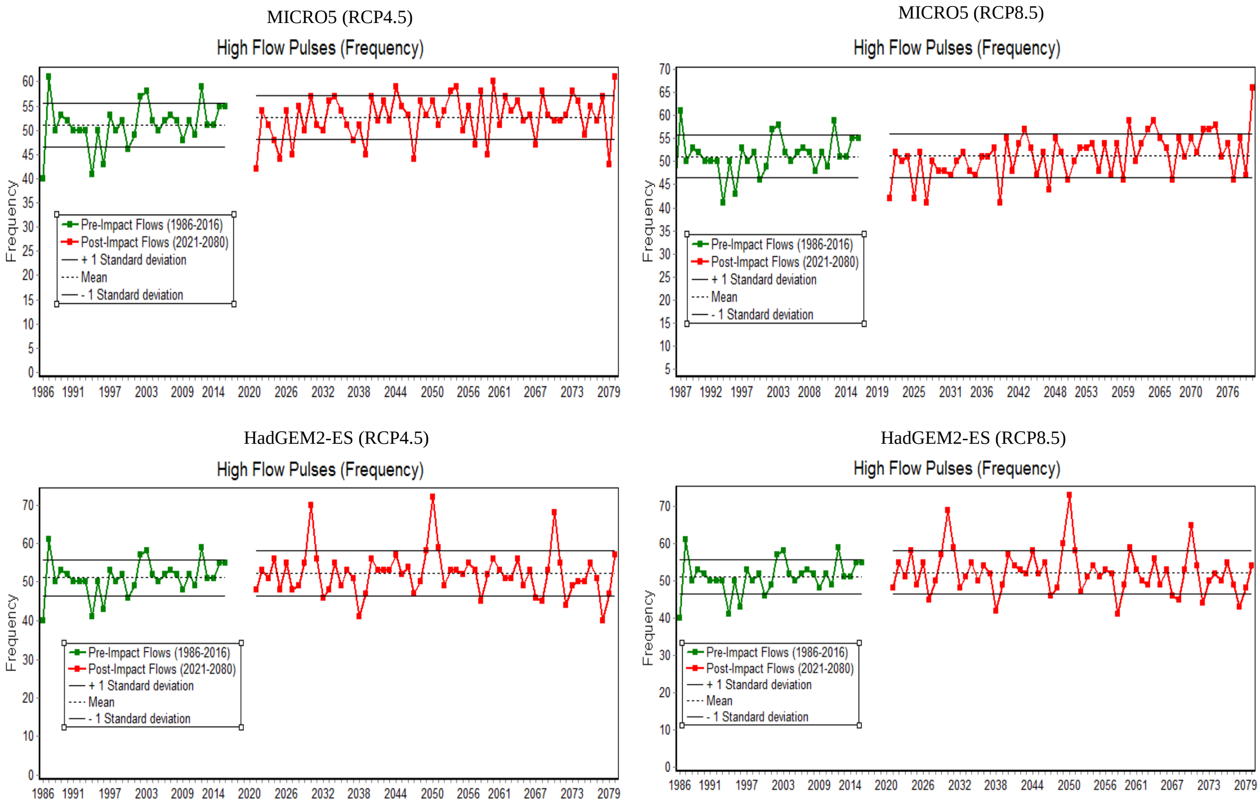

Figure 3-7. A comparison of the annual series of high pulses frequency (group 3) for the baseline period and 2061 – 2080

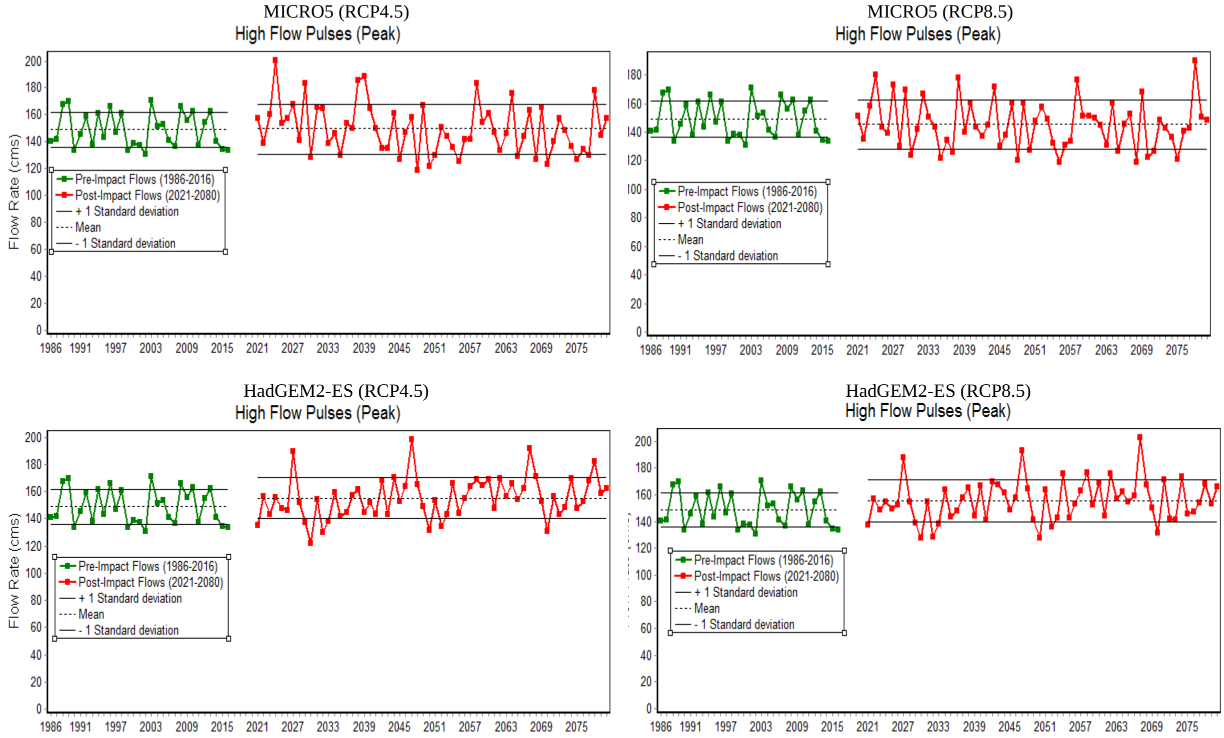

Figure 3-8. A comparison of the annual series of high pulses peaks (group 3) for the baseline period and 2061 – 2080

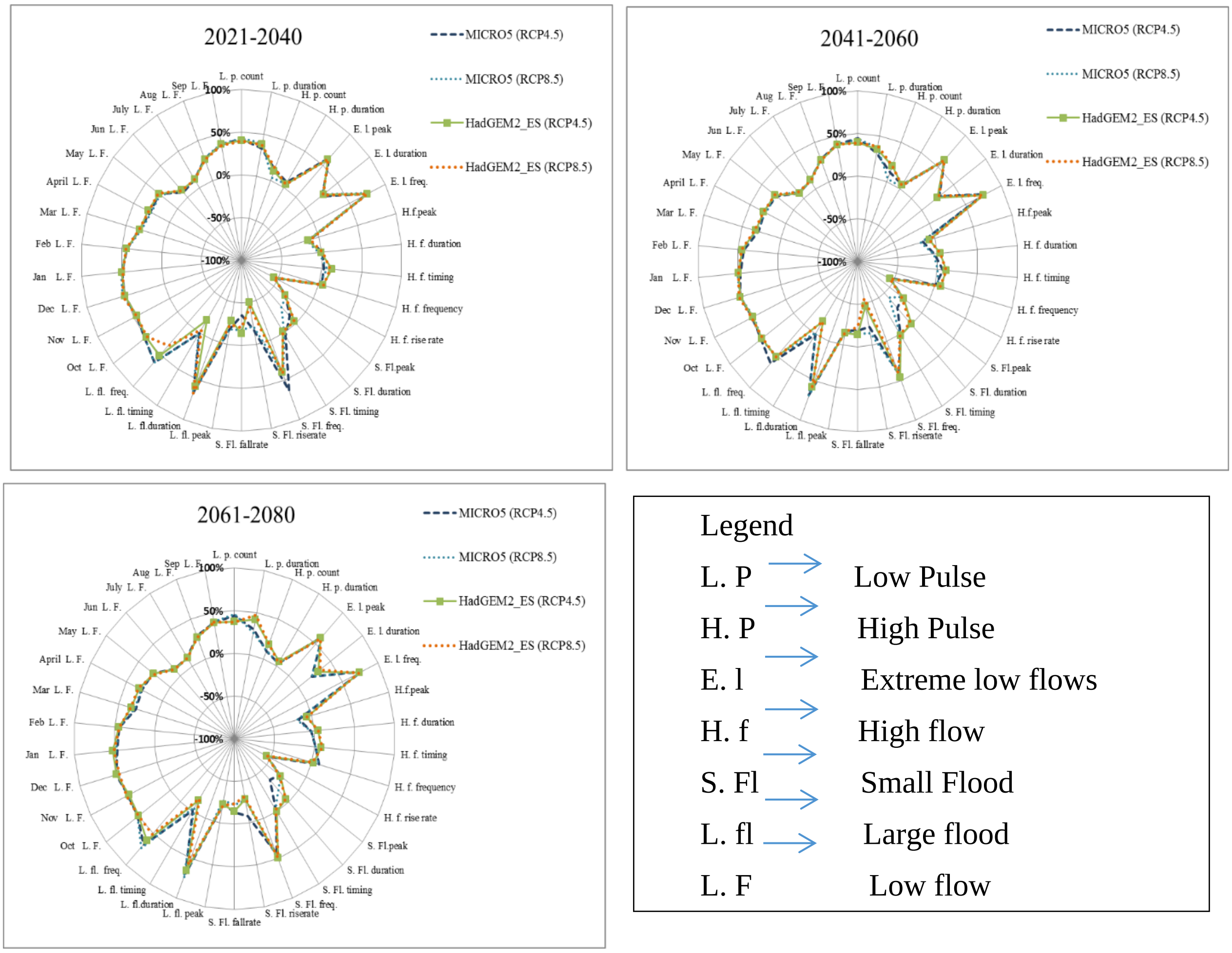

Figure 3-9 Changes in 34 indicators of IHA (Indicators of Hydrologic Alteration) and EFC (Environmental Flow Component) in percentages between baseline and future periods

The magnitude of the water condition is a measure of the suitability, or availability, of the results of this study showed different predictions of future climate change effects on the river flow. In other words, it was shown that annual discharge of Kikuchi basin is decreasing from 46 m^3/s to approximately 43 m^3/s, however; HadGEM2-ES showed it can be expected to have 1-2 m^3/s increase in streamflow within next century. To have a better vision on differences, boxplots for observed (history) and simulated mean annual inflows based on these two GCMs were provided (Figure 3-10). The median results derived from HadGEM2-ES and MICRO5 were quite similar as the observed inflow, however; there are differences between maximum and minimum of historical period and both GCMs. Based on a study done by Kudo et al. (2017) (20) there is a large uncertainty in river flow simulations in western Japan especially Kyushu which is mostly because of the puddling stage which is mainly in June, when river flows are dominated by rainfall. Moreover, precipitation changes projected by GCMs have larger uncertainty in western Japan. So, impacts of climate change on EFCs were assessed by considering uncertainties of river flow simulations.

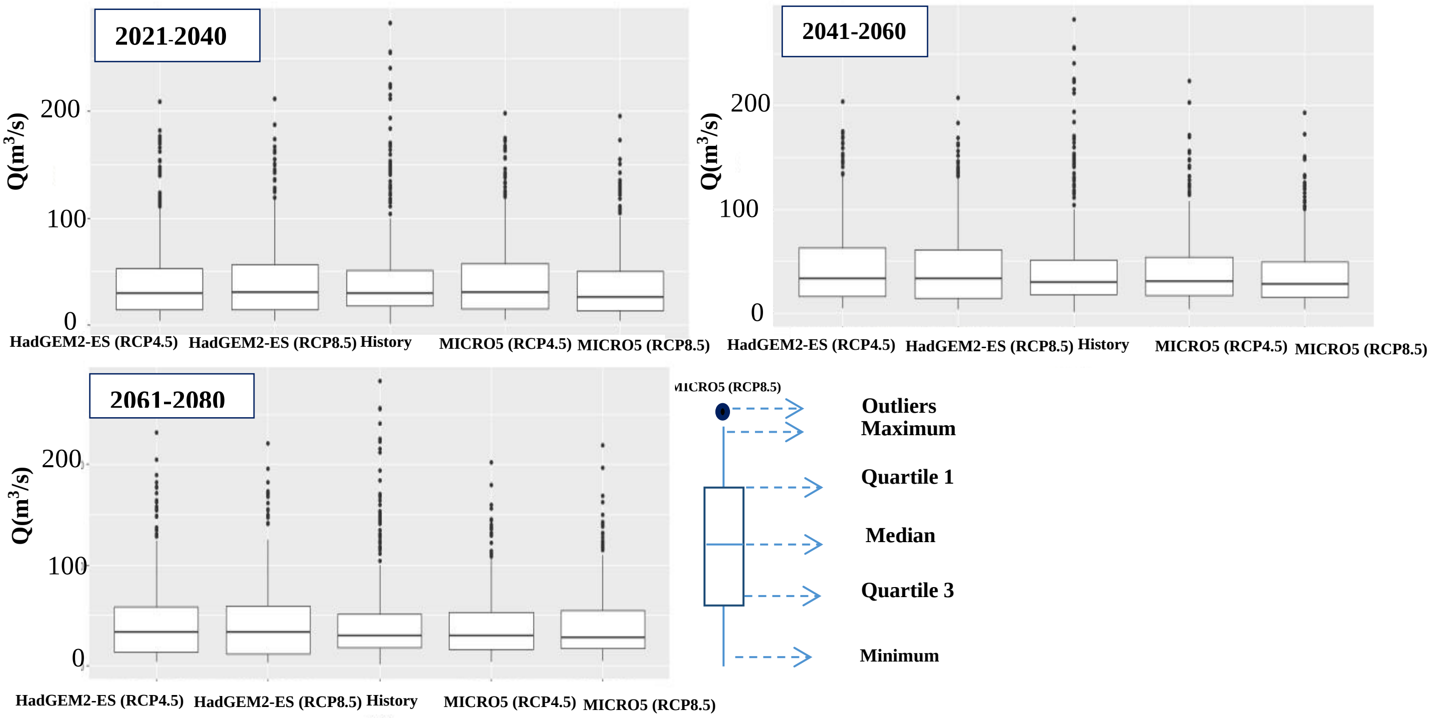

Figure 3-10. Observed (history) and simulated mean daily discharge of the Kikuchi river under GCMs models

- ***EFC* groups**

Group 1) In this group low flows above the 10th percentile of the average magnitude of monthly flows were calculated and the results showed that this parameter will increase on up to 50%. This event affects the maintenance of water temperatures, as well as dissolved oxygen (7,13).

Group 2) The 10th percentile of all low flows, known as extreme low flows, were analyzed in this group. For the Kikuchi River, the frequency of this parameter is expected to increase up to 70%, moreover; the duration of this value will rise up to 25% 2080. Therefore, it is expected that during drought periods, rivers will drop to very low levels, causing stress for many organisms (7,13).

Group 3) High-flow pulses are flows which have return intervals of less than two years. For our case study the duration of this parameter is expected to be same as baseline period, nevertheless; the count of high pulses is increasing which will necessitate strategies for maintaining the physical shape of river channels. In addition, the size of streambed substrates (e.g. sand, gravel, cobble) will change during this 100 years, which is one of most important variables for aquatic habitat suitability (13,16).

Group 4) Small floods are events with return intervals of 2–5 years whose rise rate, from our case study, the frequency of this variable is predicted to be twice as much as baseline period in the future. As a result, fish spawning in floodplain as well as feeding sites would be affected by climate change (7,13).

Group 5) In this group large floods were analyzed, which are events that have peaks corresponding to a five year return interval event or greater. The frequency of this parameter is expected to grow about 60% within next century. As a consequence, river structure and physical shape will change, and organism materials (food) will be removed from the river channel (7).

3-4. Conclusion

The present study assessed the impact of climate change on hydrological indicators and environmental components, as well as water temperature in the Kikuchi River basin. SWAT model was used as a hydrological model to simulate the flow of the Kikuchi River. The hydrological and environmental effects of climate change on our case study was analyzed by using IHA software. Comparative analyses were conducted between a baseline period (1986–2016) and climate change periods (2021–2040, 2041–2060, & 2061–2080) to understand how river flow dynamics will affect the health of the riverine ecosystem.

Under two RCPs (4.5 & 8.5), it is expected to have less precipitation and less river flow in Kikuchi basin, however; it is also predicted to have an increase in both these variables under HadGEM2-Es (RCP 4.5 & 8.5) for 2041-2060, because of having uncertainties in GCMs. Based on the SWAT model output, the discharge of the river is predicted to decrease from 46 m^3/s during the baseline period, to approximately 43 m^3/s over the next 100 years. Moreover, the frequency of extreme low flows and count of high flow pulses are two parameters of EFCs which would be affected more by climate change in comparison with other indicators. For both of these parameters it is expected to have 60% increases within next century.

Low and high flows imply that the life cycle of many aquatic species may get disrupted during various stages such as spawning. Moreover, it will affect their movement onto the floodplains for feeding and reproduction. These changes will put additional stress leading to a risk of ecological change in a riverine ecosystem already affected by anthropogenic interference (8). So, it is important to think up strategies for maintaining a river discharge using minimum criteria to sustain diverse fish communities. On the other hand increasing in high flow pulses will affect habitat patterns at river-wide scales (as a hydraulic parameter) influencing river ecosystem (21) .

Therefore, in the next chapter impact of climate change on hydraulic parameters including water depth and water velocity has been analyzed to understand how hydrological changes will affect these parameters.

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Table of Contents

Chapter 4: Projecting impact of climate change on hydraulic river flow parameters

4-1. Introduction

To have an efficient water management planning and decision-making, forecasting or modeling the aquatic habitat including the impact of water takeoffs, river training or the effects of climate change would be so helpful. In this regards, the models which are mainly based on hydrological, morphological, and hydraulic parameters affecting the distribution and abundance of organisms in the stream are being widely used (1).

There are different methods to model riverine ecosystem, such as SWAT model which is an eco-hydrological model providing discharge and water quality time series at the catchment scale. The 1-D hydraulic model HEC-RAS is another method to develop a rating curve for the downstream end of the study reach predicting the water level for given discharges. Moreover, 2-D hydrodynamic models such as iRIC (International River Interface Cooperative) are also available for which discharge and water level are necessary input parameters. So that, predicting hydraulic parameters including flow velocity and water depth for all raster cells of a two-dimensional computational grid is possible (2).

4-1-1. iRIC (International River Interface Cooperative)

This software has 17 solvers some of which are widely used for hydrological aims in recent years, especially models of Nays2DH, River2D,and FaSTMECH (3–5). To simulate horizontal two-dimensional (2D) flow, Nays2DH was developed which is also modeling sediment transport, and morphological changes of bed and banks in rivers. There are lots of important parameters including: the location, volume and timing of floods which can be predicted by Nays2DH. So that, results of this solver have been widely used for disaster prevention, river management planning as well as restoration projects (6).

4-1-2. Habitat classification

Generally, there are three main habitat types known as riffle, run and pool (Figure 4-1) which are distinguished by ecologists. Identification of these three habitat types is considering bed material size, water surface slope, range of water depth and velocities, bed topography, and Froude number (7). Based on Jowett's (1993)(8), habitat types would be recognizable using Froude number, water surface slope and velocity/depth ratio (7).

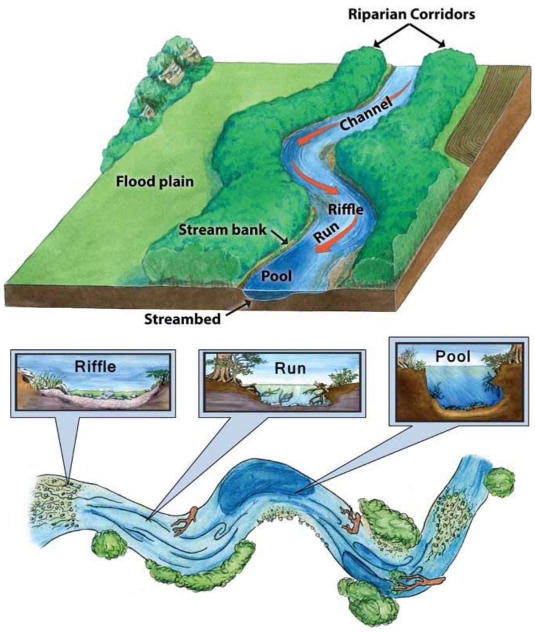


Figure 4-1 Pool, Run and riffle in a river stream (9)

In this chapter, three different habitat types including pool(deep water with a smooth water surface), run (fast water, usually deeper than a riffle), and riffle (fast water with a shallow water surface) were recognized based on Jowett's methodology (10). After that, changes in water depth and water velocity in each of these habitat types affected by climate change were analyzed. In this regard, Nays2DH solver in the iRIC model was used whose outputs are as input for EvaTrip solver to assess the habitat suitability (chapter5). Method

4-1-3. Nays2DH

The basic method of this solver is that the equations are given in a channel-fitted orthogonal curvilinear coordinate system. This coordinate system described only by a centerline path, width, and spatial resolution which make a grid on the river. The solver fulfillments a two-dimensional calculation for vertically averaged flow using a variant of the SIMPLE technique which is considering upwind differencing, differential relaxation on water-surface elevation and vertically averaged velocity (6). Figure 4-2 shows the Nays2DH windows.

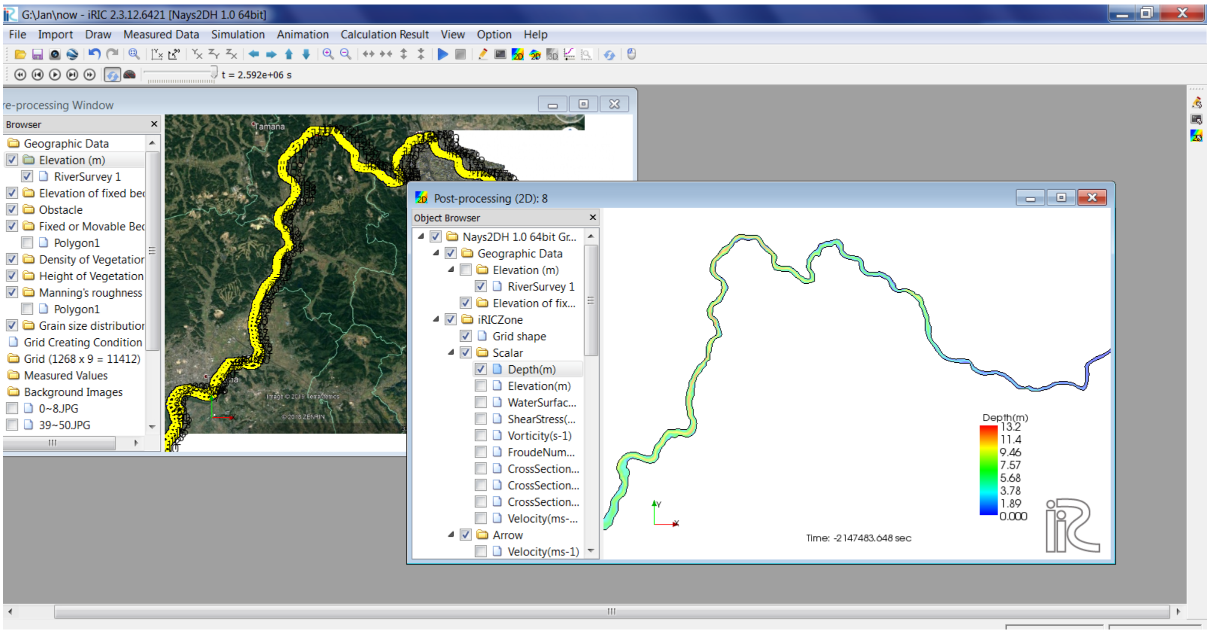


Figure 4-2 iRIC, Nays2DH solver windows

In order to operate Nays2DH solver has different steps which are shown in Figure 4-3:

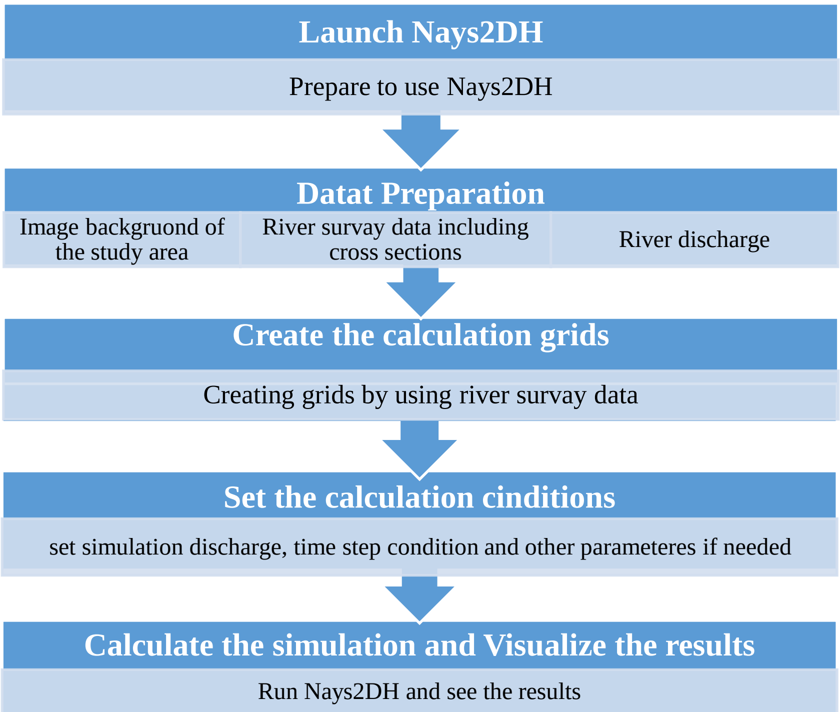


Figure 4-3 Procedure for operating the Nays2DH solver with iRIC

Basic equations of two dimensional plane flow at orthogonal coordinates (x, y) are transformed into general coordinates (ξ, η) so that it becomes possible to set a calculation mesh of any shape (5,11) (Figure 4-4). So that for each cell information on hydraulic parameters including water depth (m), water velocity (m/s), Froude number and water surface elevation (m).

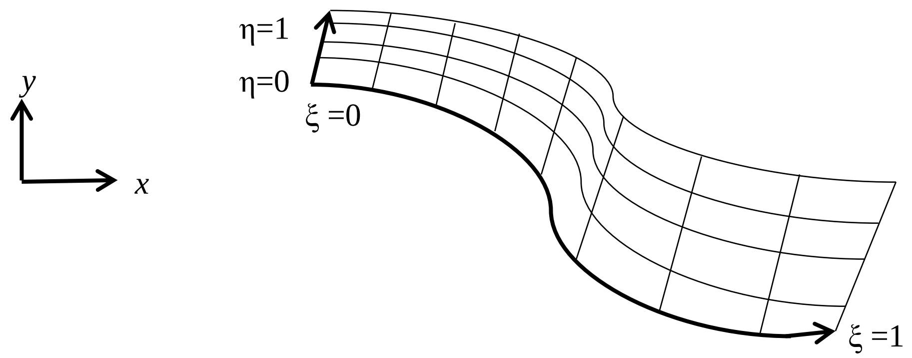


Figure 4-4 Definition diagram for the plane coordinate system used in the model: the axes of an orthogonal Cartesian coordinate system are *x* and *y*. the axes of a non-dimensional generalized orthogonal coordinate system are ξ, and η.

In this study data about the river survey and background image achieved from Kukamoto University. Moreover, Data of river flow in baseline period and future period obtained from SWAT model.

4-1-4. Habitat classification methodology

To have a better vision on how climate change is affecting hydraulic parameters, the river flow was divided to three different habitat types including Pool, Run and Riffle. This classification was done based on results of Jowett’s studies (7).

Table 4-1 Habitat type classification

Model	Pool	Run	Riffle
Froude discriminant	<0.18	0.18-0.41	>0.41
SI discriminant	<0.0039	0.0039-0.0099	>0.0099
V/D discriminant	<1.24	1.24-3.20	>3.20
Fr & SL rule	Fr<0.18	Fr>0.18 & SI≤0.009	Fr≥0.18 & SI>0.009
V/D & SI rule	V/D<1.24	V/D≥1.24 & SI≤0.0099	V/D≥1.24 & SI>0.0099

4-2. Results and Discussion

In this study after projecting river flow based on two different GCMs (MICRO5 and HadGEM2-ES) under RCP4.5 and RCP 8.5, river flow for future periods (2021-2040, 2041-2060, 2061-2080) were simulated using SWAT model. Based on the result of the previous chapter, it was found out that the highest value of streamflow is expected to happen under HadGEM2-ES (RCP4.5) and the lowest value is under MICRO5 (RCP8.5) on 2041-2060. So in this chapter changes in water velocity and water depth of whole the river, upstream, middle stream and downstream (Figure 4-5) will be analyzed. The months of August, January and July were chosen to study as they are representative of the month of the highest water level, lowest water level and important time for fish spawning, respectively.

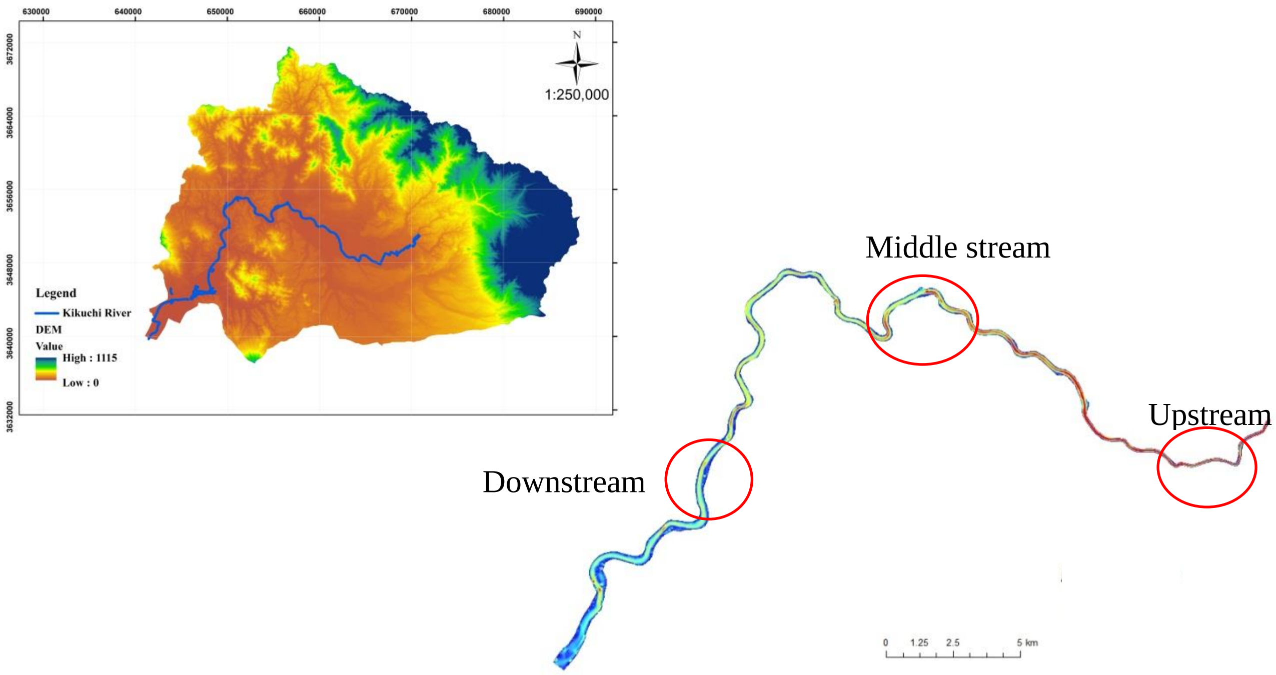


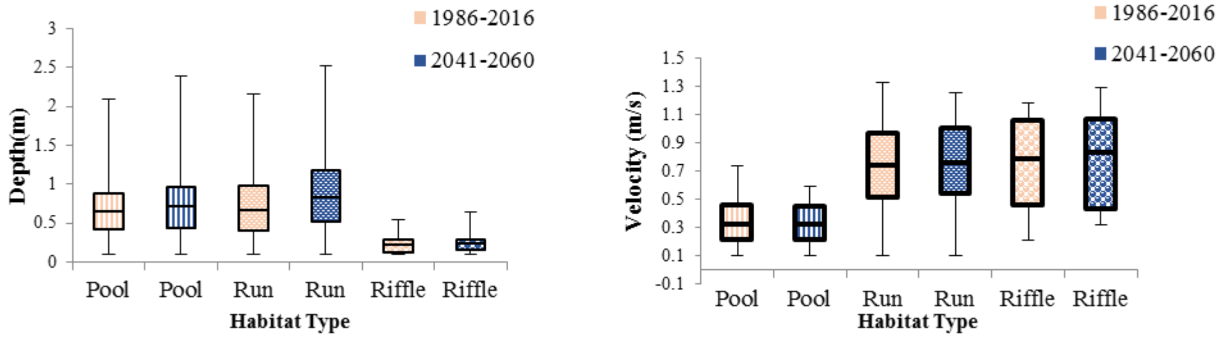
Figure 4-5 Studied areas of the Kikuchi River

4-2-1. Hydraulic changes influenced by climate change on August

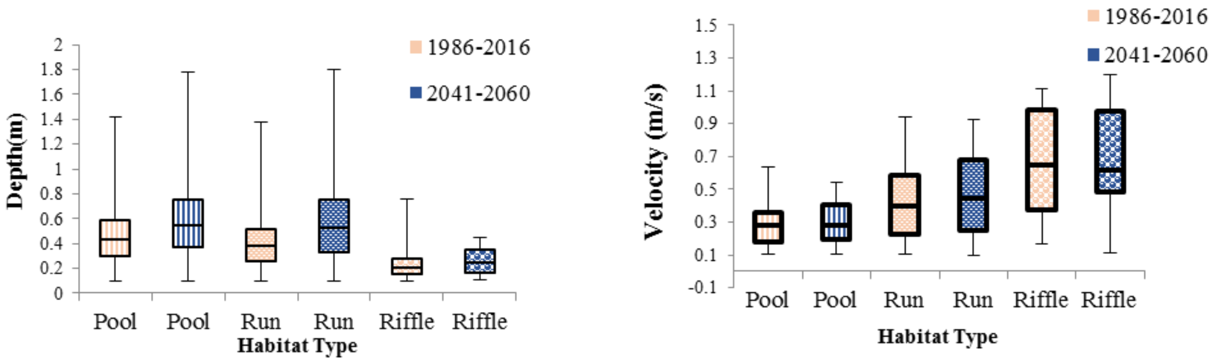
- *Whole the river*

As a general view on the whole of the Kikuchi river, it is expected to increase in the water depth and decrease in the water velocity in August by 2060. So that, the median of water depth will increase up to about 0.2 (m) and the median of velocity will decrease around 0.01 (m/s), respectively, when the river flow is in its average value. These rise and reduction are more sensible in their maximum values which are about 0.5 (m) and 0.2 (m/s) for depth and velocity, respectively. Notably, that maximum value of the water velocity is projected to increase up to 0.2 (m/s) (Figure 4-6 (a)).

The result of iRIC model using minimum value of discharge on August showed the median and maximum of the water depth are expected to increase up to 0.2 (m) and 0.4 (m), respectively, in pool and run habitat type. However, the maximum value of water depth in riffle part is reducing about 0.4 (m). There is a slight reduction in the median of the water velocity, while; this decrease in its maximum value is about 0.2 (m/s) in pool and run river sections. Again for riffle, maximum water velocity is expected to have a smooth increase (Figure 4-6 (b)).



a)



b)

Figure 4-6 Impact of climate change on water depth and velocity on August based on HadGEM2-ES (RCP4.5): a) at mean value of discharge, b) at minimum value of discharge

- *Upstream*

Based on the iRIC result after running this program by using the maximum value of river flow, water depth is decreasing in pool habitat type and it is increasing for run and riffle sections up to 1 (m). Water velocity is also expected to decrease, however; the median of this parameter for riffle part is increasing by 2060 (Figure 4-7 (a)). So in flood situation, it is projected stronger river flow increase as both water depth and water velocity are growing up.

When I used average value of river flow on August, results showed water depth and velocity will be approximately same as baseline period for pool section, however; these hydraulic parameters are expected to increase up to 0.7 (m) in water depth and 0.3 (m/s) in water velocity (Figure 4-7 (b)).

Using the minimum value of discharge in August illustrated that water depth in all three habitat types is an increase in its median and maximum about 0.2 (m) and 0.6 (m), respectively. This increase is also happening in water velocity for riffle section about 0.8 (m/s), however; this parameter is projected to slightly decrease for pool and run habitat type (Figure 4-7 (c)). Figure 4-18 which is available in the appendix shows a better vision of these changes in this part of the Kikuchi river.

- *Middle stream*

At maximum value of river flow, water depth and velocity are slightly increasing in pool habitat type in the middle of streamflow. This increase in the water depth is up to 0.3 (m) in run section Figure 4-8 (a).

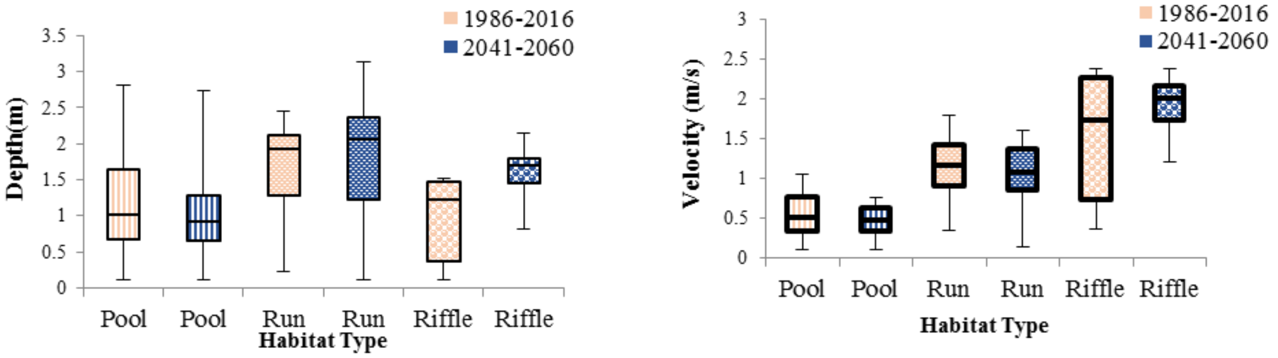
Although water depth and velocity are expected to be approximately the same at an average value of discharge in the pool section, these hydraulic parameters are increasing and decreasing about 0.3 (m) and 0.1 (m/s) in the run section, respectively. In riffle section, there will be a rise in both depth (up to 0.5 (m)) and velocity (about 0.7 (m/s)) (Figure 4-8(b)).

It seems the maximum changes in these parameters will happen in the minimum value of the river flow. In other words, in all three habitat types, the water depth will increase 0.2-0.4 (m) and the water velocity is rising 0.1 -0.5 (m/s) (Figure 4-8 (c)).

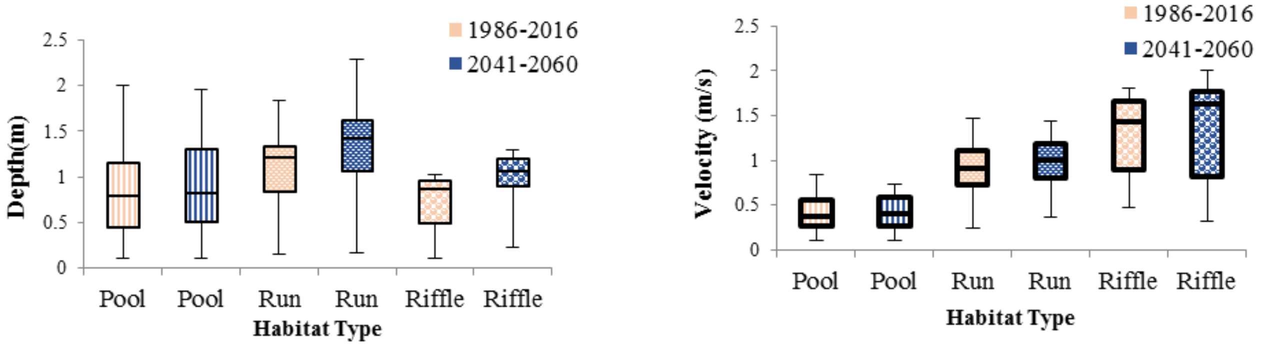
- *Downstream*

At the maximum value of discharge for downstream of the river, water depth and velocity are expected to have a smooth increase in all three habitat types (Figure 4-9 (a)). This slight rise is also feasible when the river flow is in its average value, however; the most gain is happening for the water velocity in the run section which is up to 0.2 (m/s). It is notable that although water depth in the riffle part is increasing, the water velocity has a slight reduction (Figure 4-9 (b)).

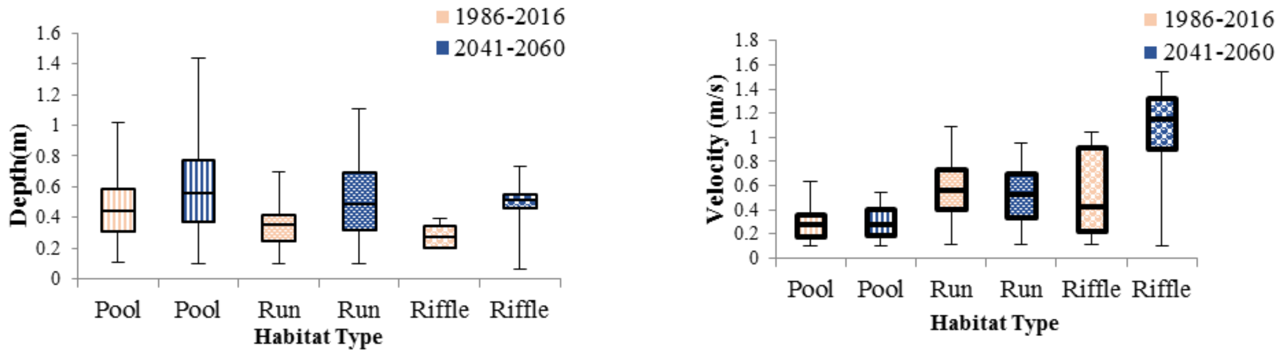
Again maximum changes in the hydraulic parameters are related to when river flow is in its minimum value. Water depth is expected to increase up to 0.4 (m) in all three different studied habitat types. While water velocity is expected to have a slight reduction except in the riffle section in which water velocity will increase up to (0.5 m/s) (Figure 4-9 (c)).



a)

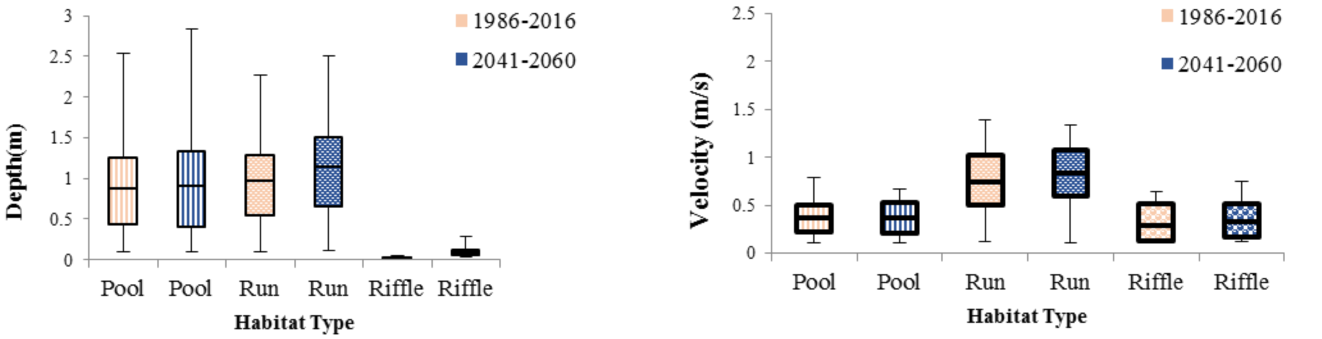


b)

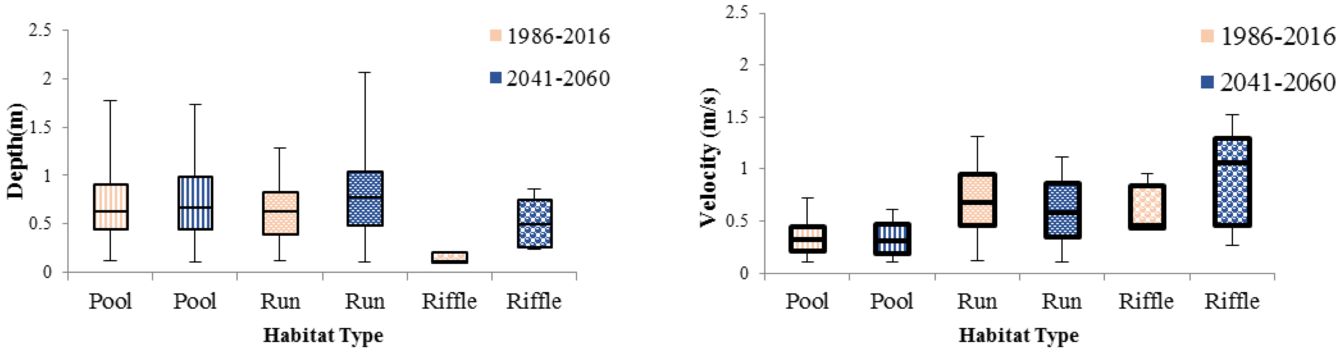


c)

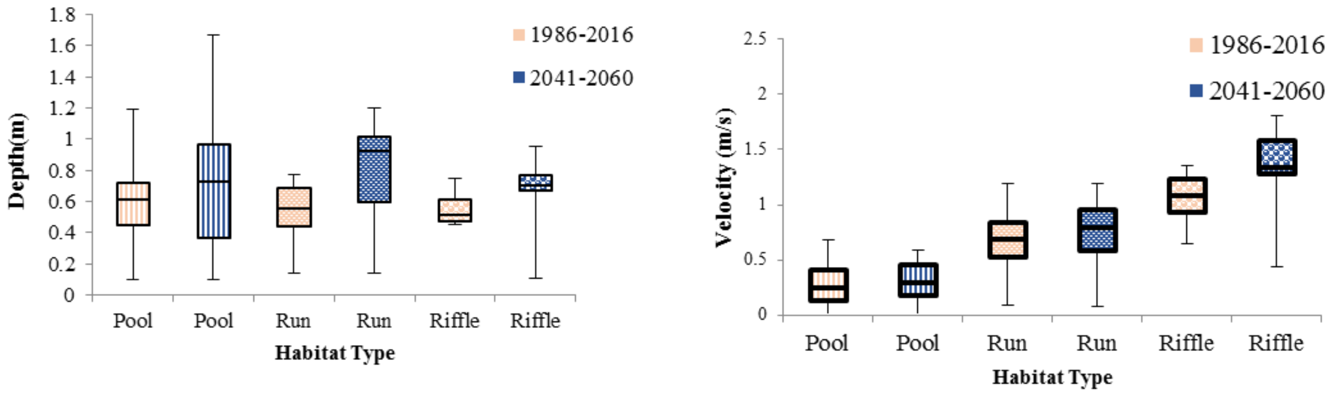
Figure 4-7 Impact of climate change on water depth and velocity on August based on HadGEM2-ES (RCP4.5) in upstream: a) at maximum value of discharge, b) at mean value of discharge, c) at minimum value of discharge



a)

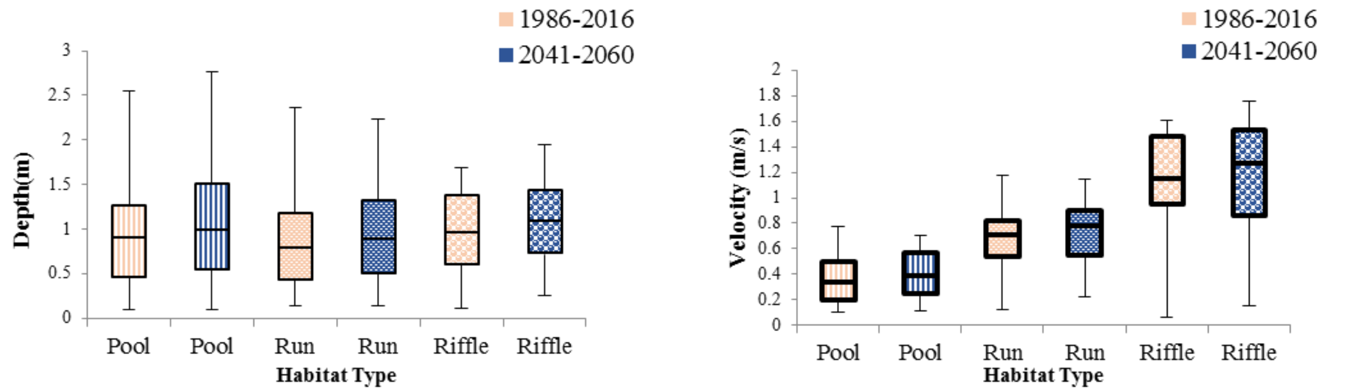


b)

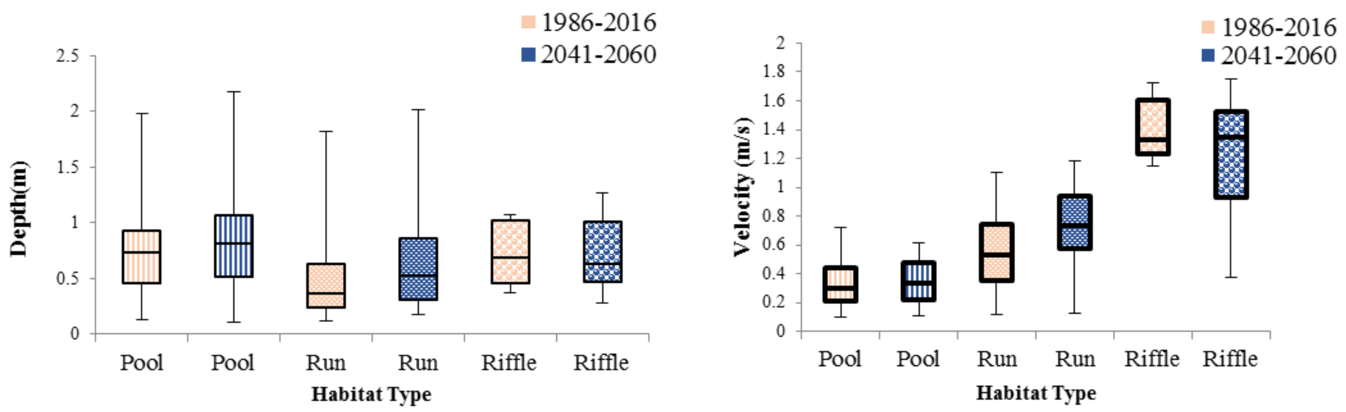


c)

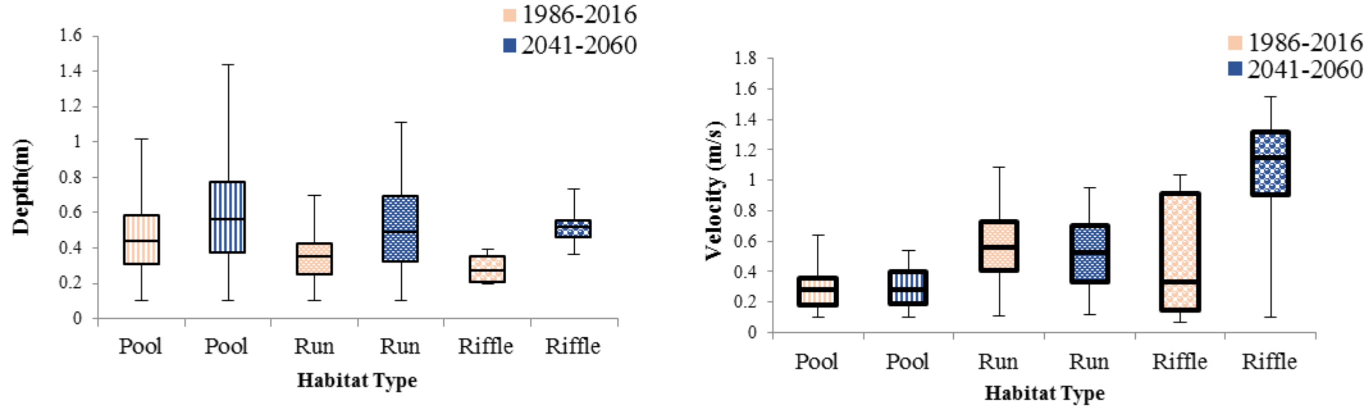
Figure 4-8 Impact of climate change on water depth and velocity on August based on HadGEM2-ES (RCP4.5) in middle stream: a) at maximum value of discharge, b) at mean value of discharge, c) at minimum value of discharge



a)



b)



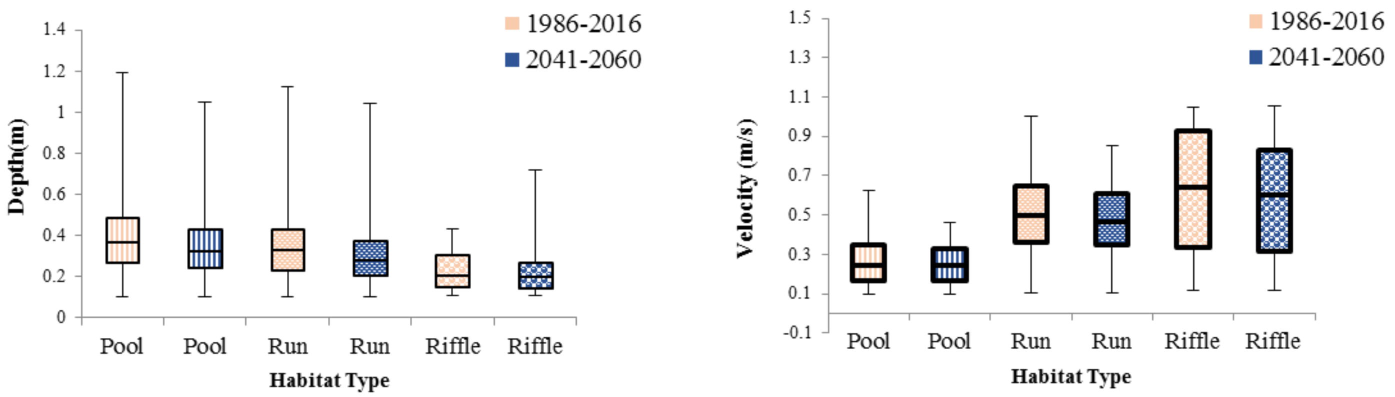
c)

Figure 4-9 Impact of climate change on water depth and velocity on August based on HadGEM2-ES (RCP4.5) in downstream: a) at maximum value of discharge, b) at mean value of discharge, c) at minimum value of discharge

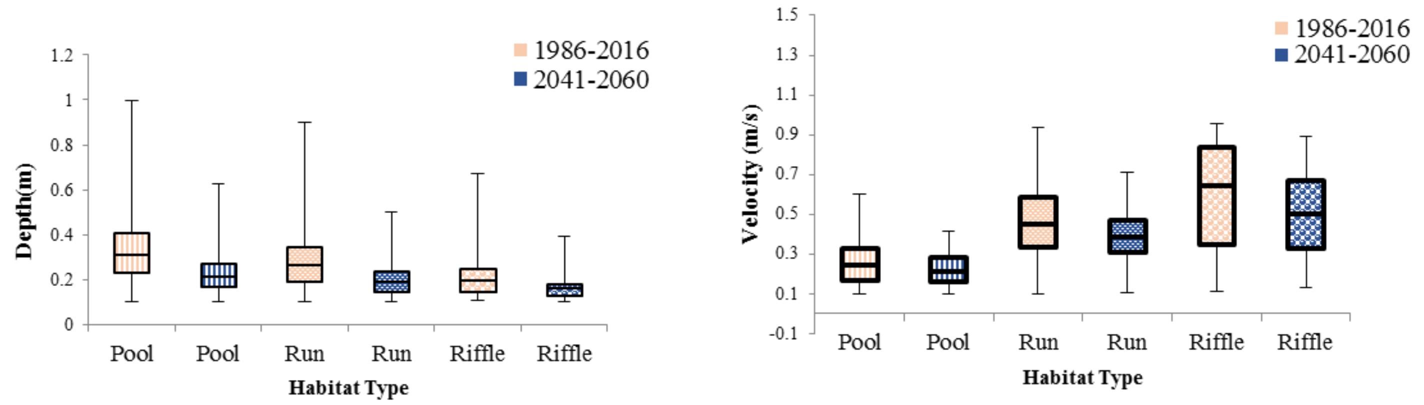
4-2-2. Hydraulic changes influenced by climate change on January

- *Whole* the river

Generally, water depth and water velocity are expected to decrease on January. This reduction is more tangible when the iRIC model was run for minimum value of river flow. So the median of water depth and water velocity are projected to reduce up to 0.2 (m) and 0.2 (m/s), respectively (Figure 4-10).



a)



b)

Figure 4-10 Impact of climate change on water depth and velocity on January based on MICRO5 (RCP8.5): a) at mean value of discharge, b) at minimum value of discharge

- *Upstream*

Figure 4-11 shows that the hydraulic parameters are expected to decrease in both average and minimum values of discharge. However, this reduction is higher which is up to 0.2 (m) in the water depth and 0.1 (m/s) in the water velocity. It is notable that although the values of these parameters are reducing but the median of water velocity in riffle part of the river is increasing up to 0.3 (m/s).

- *Middle stream*

As what it is going on in the upstream, water depth and velocity are expected to decrease in middle stream, as well. This reduction is in its higher value when the minimum value of river flow was introduced to the model (Figure 4-12).

- *Downstream*

At downstream also water depth and velocity are expected to decrease and this reduction is in its higher value when the minimum value of river flow was introduced to the model, especially for the water velocity in the riffle section (Figure 4-13).

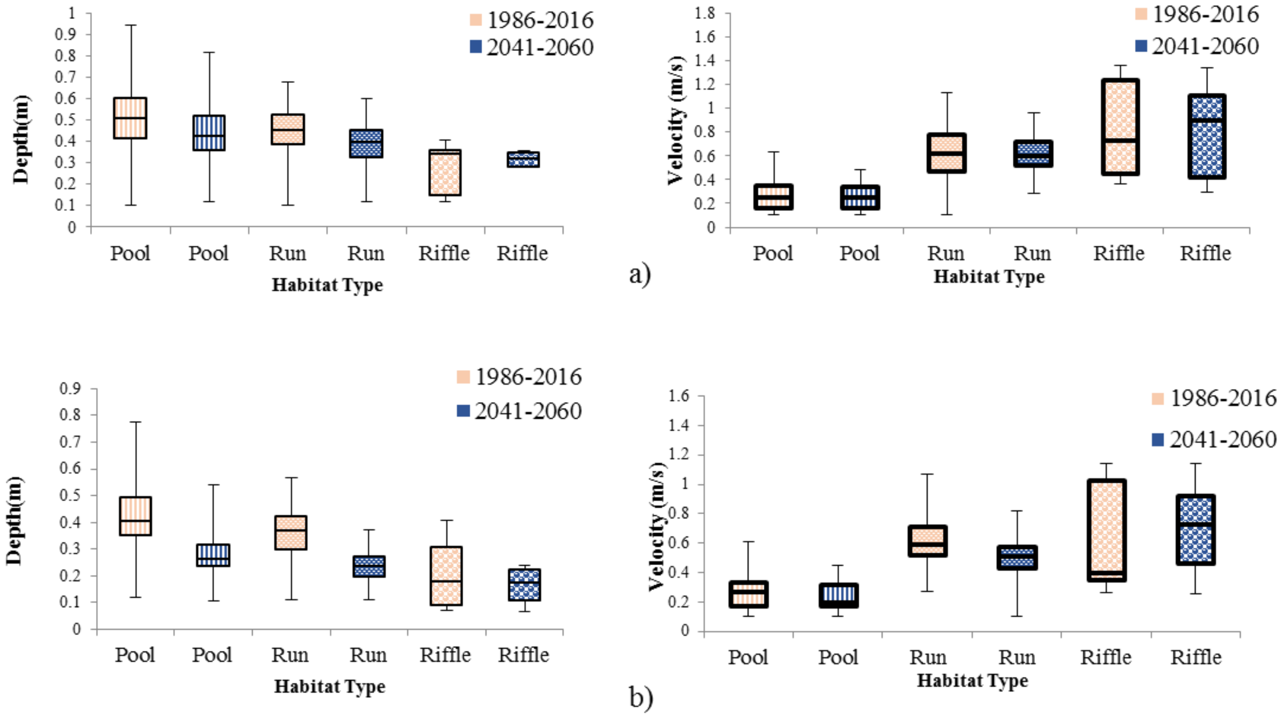


Figure 4-11 Impact of climate change on water depth and velocity on January based on MICRO5 (RCP8.5) at upstream: a) at mean value of discharge, b) at minimum value of discharge

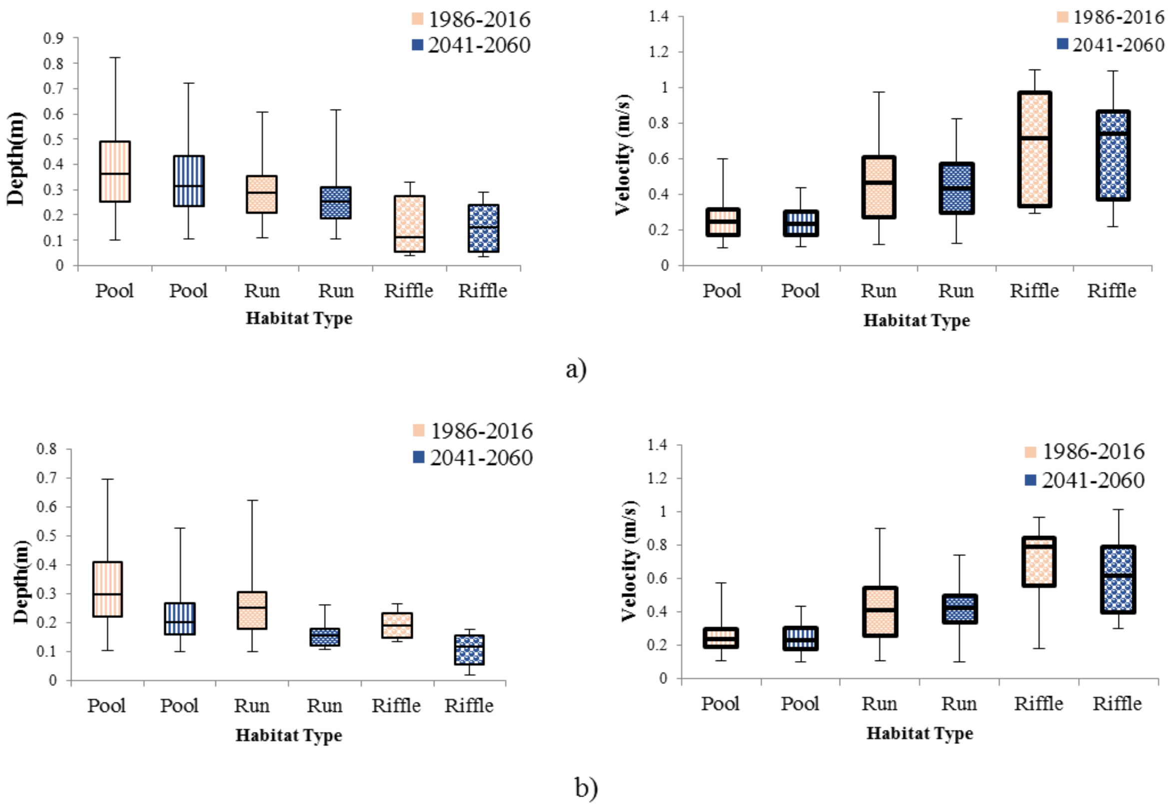


Figure 4-12 Impact of climate change on water depth and velocity on January based on MICRO5 (RCP8.5) at middle stream: a) at mean value of discharge, b) at minimum value of discharge

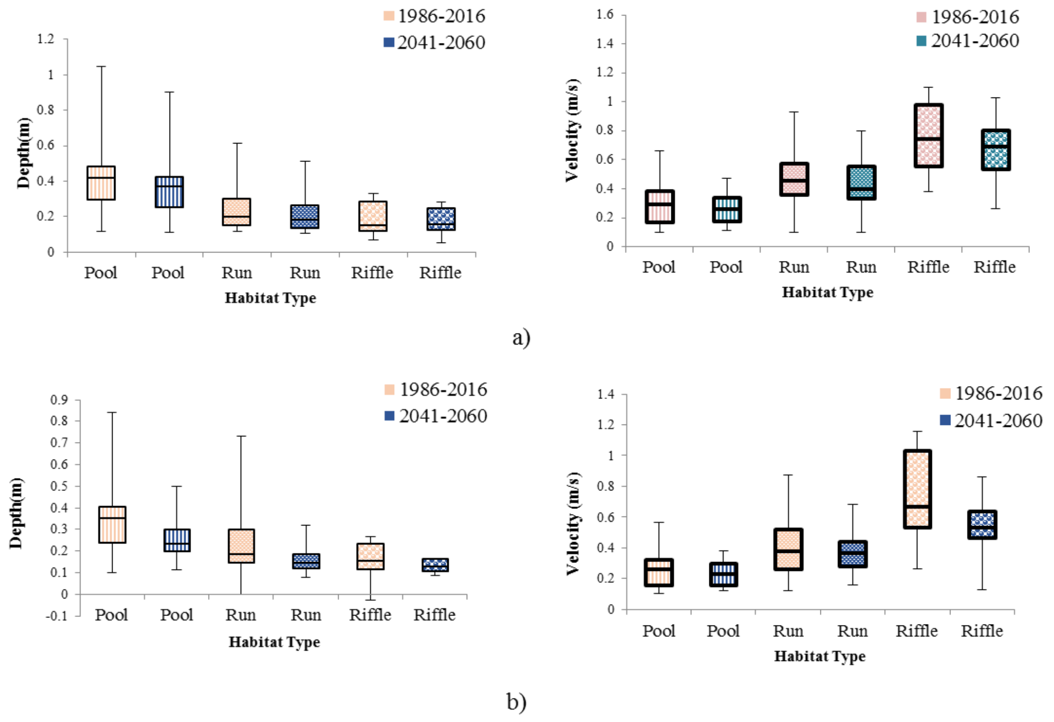


Figure 4-13 Impact of climate change on water depth and velocity on January based on MICRO5 (RCP8.5) at downstream: a) at mean value of discharge, b) at minimum value of discharge

4-2-3. Hydraulic changes influenced by climate change on July

- *Whole the river*

Figure 4-14 shows that water depth and velocity are slightly decreasing when the minimum value of discharge was introduced to the model, by 2060. However, there is 0.2 (m/s) increases in water velocity at riffle part.

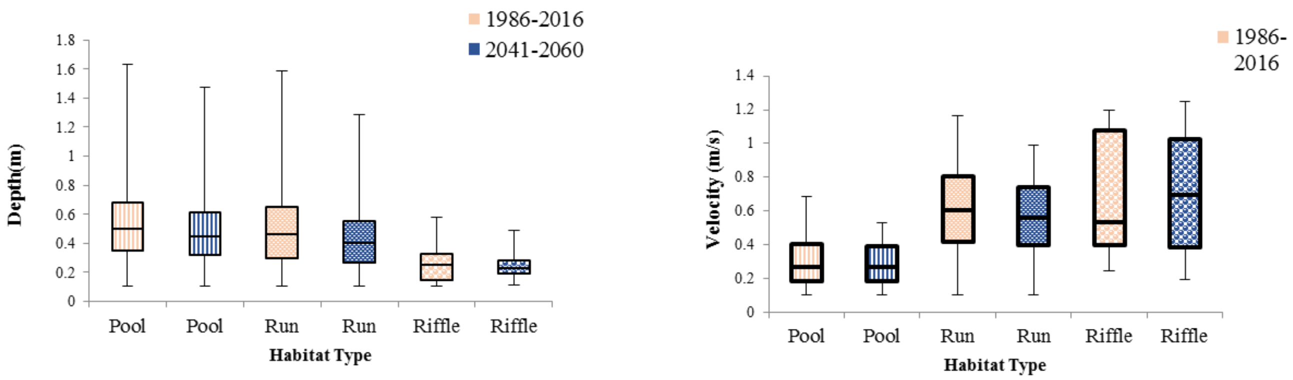


Figure 4-14 Impact of climate change on water depth and velocity on July based on MICRO5 (RCP8.5) at minimum value of discharge

Based on our result, this reduction in water depth and velocity is expected to be same for the other three parts of the river in the future (Figure 4-15 _ Figure 4-17).

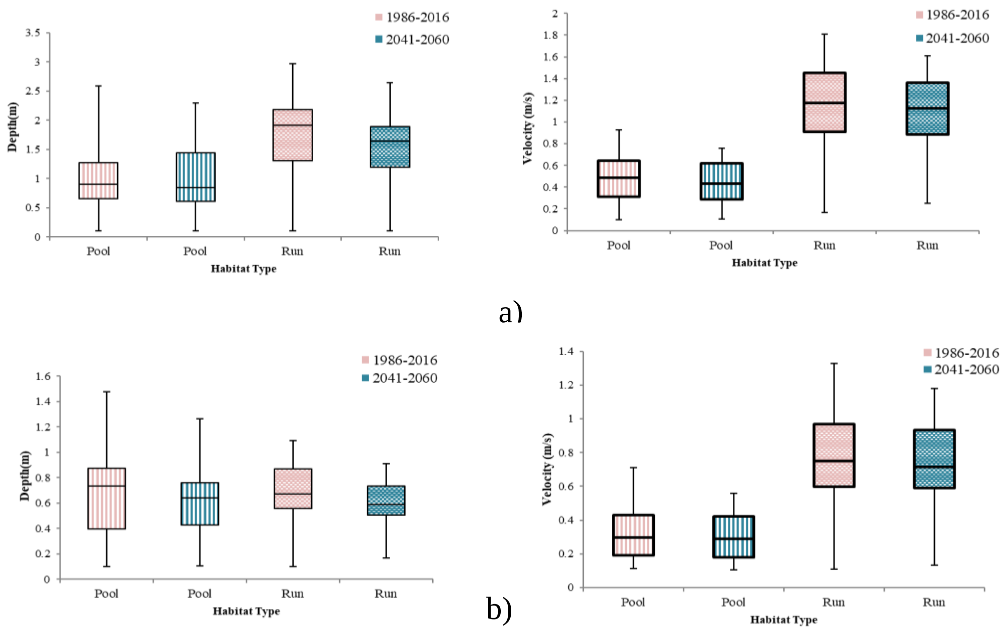
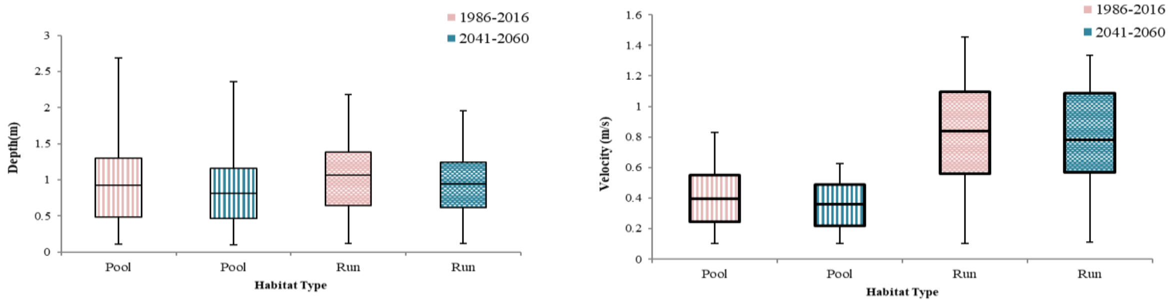
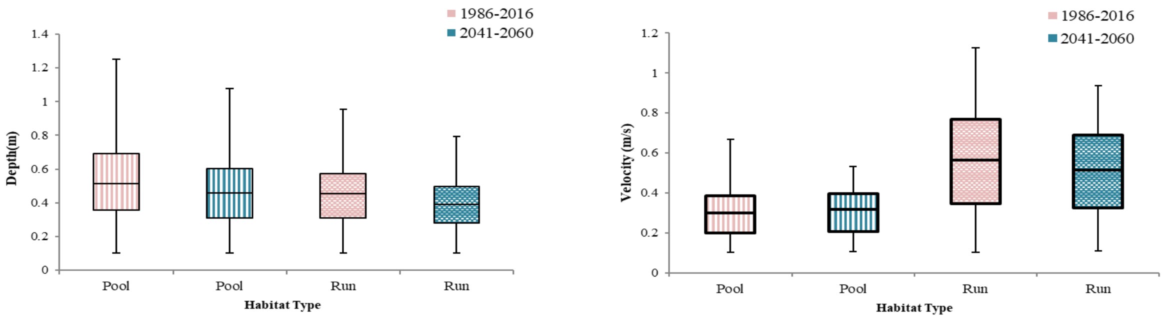


Figure 4-15 Impact of climate change on water depth and velocity on July based on MICRO5 (RCP8.5) at upstream: a) at mean value of discharge, b) at minimum value of discharge

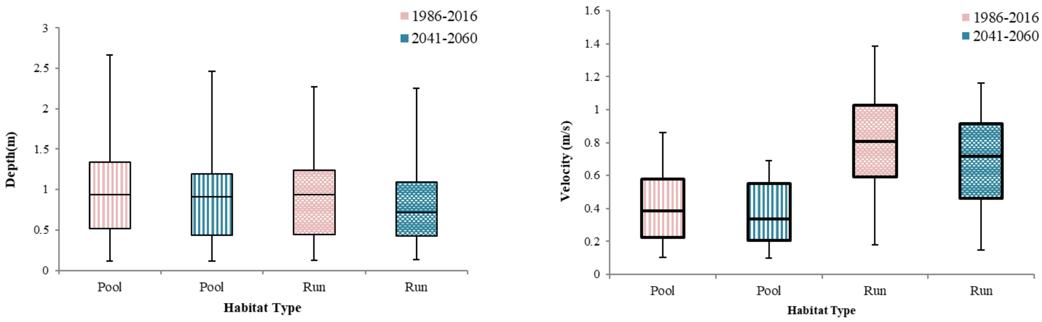


a)

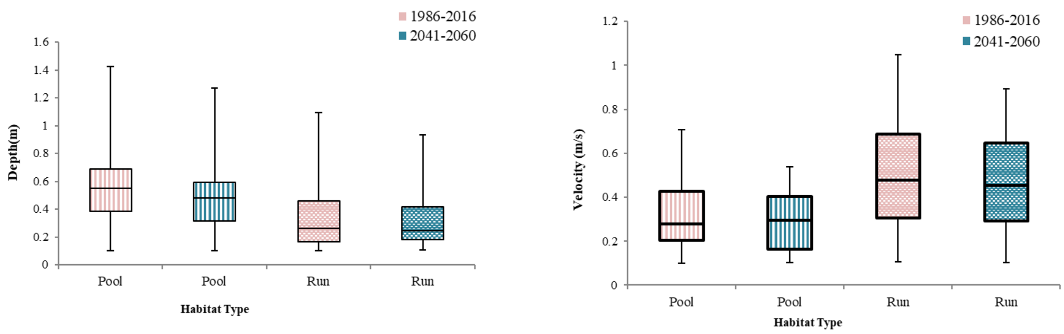


b)

Figure 4-16 Impact of climate change on water depth and velocity on July based on MICRO5 (RCP8.5) at middle stream: a) at mean value of discharge, b) at minimum value of discharge



a)



b)

Figure 4-17 Impact of climate change on water depth and velocity on July based on MICRO5 (RCP8.5) at downstream: a) at mean value of discharge, b) at minimum value of discharge

4-3. Conclusions

The main purpose of this chapter was analyzing how climate change is affecting hydraulic parameters in the Kikuchi river, by 2060. The result from previous chapter illustrated that highest and lowest level of river flow are related to projections from HadGEM2-ES (RCP4.5) and MICRO5 (RCP8.5) in 2041-2060, respectively. So in this chapter the output of SWAT model from these two GCMs was used to run Nays2DH solver in iRIC software for three months including August, January and July.

Results showed the water depth and velocity is expected to decrease on January and July, however; there will be expectations for having stronger flood on August which is because of increasing the water depth and water velocity by 2060. Floods will have different side effects on ecosystem services and it is possible to reduce them (12). On the other hand, it is predicted to have new parts of river which will have water in the future specially in maximum value of river flow. It is important to know if these new cells will increase habitat suitability for target fish in the future despite of increasing in water depth and water velocity.

The hydraulic parameters are predicted to decrease in the future on June and July. So it is necessary to know to what extend these reductions will affect habitat suitability for Oikawa and Kawamutsu fish which our target fish and indexes of the river health.

In the next chapter, beside studies on these questions I will compare habitat suitability changes in the future with and without considering water temperature. This will be helpful to see to what extend hydraulic parameters are affecting HSI and how much important it is considering water temperature in habitat simulations. In other words, as previous studied showed Oikawa and Kawamutsu are adaptive species and changes in water depth, water velocity and sediments has not affected their habitat suitability (13,14), I want to know if these range of changes in hydraulic parameters in our case study will affect their HIS. Secondly, I want to know to what extend considering water temperature in habitat suitability simulations will affect Oikawa and Kawamutsu HSIs.

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Appendix

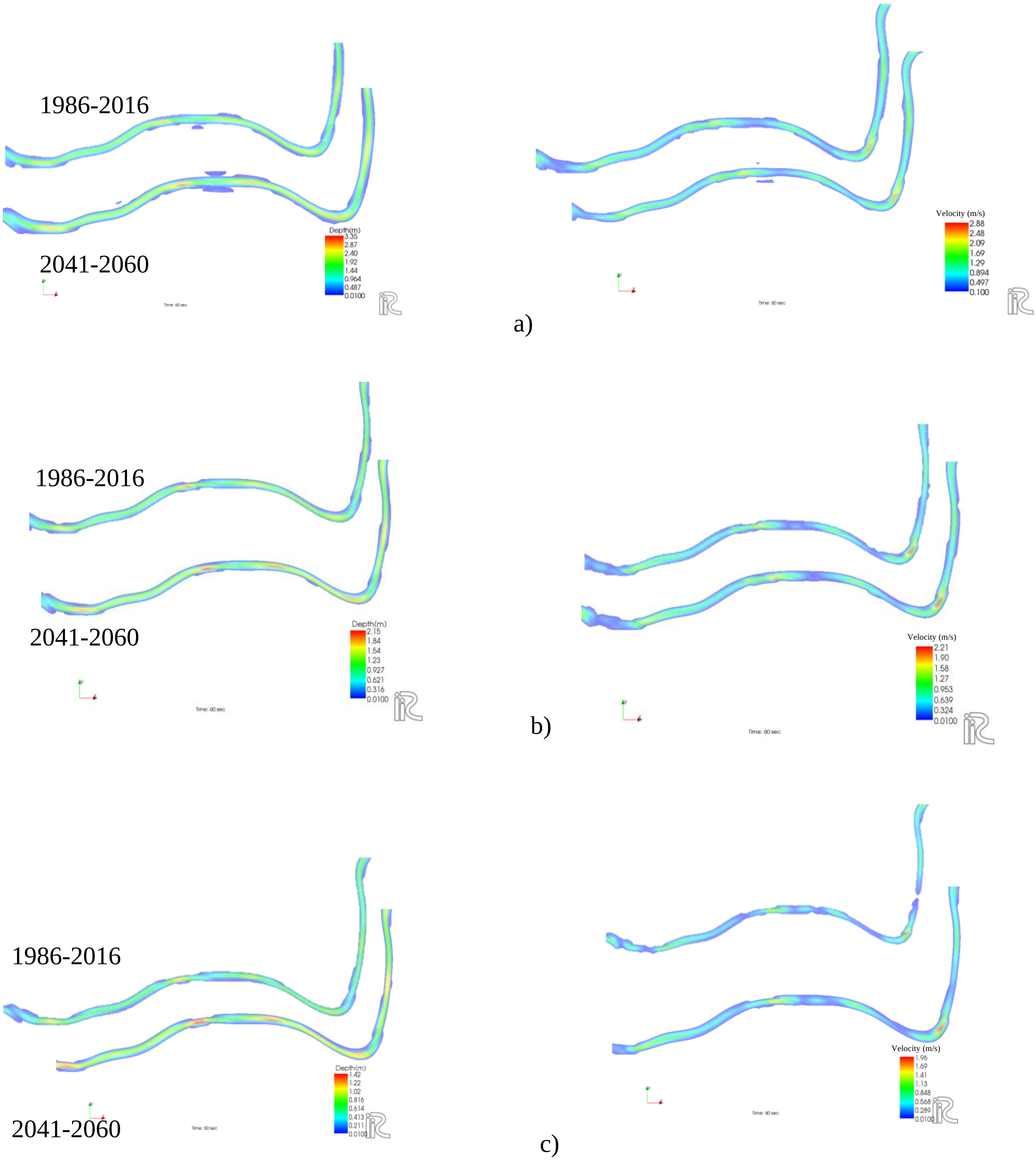


Figure 4-18 Visualized impact of climate change on water depth and velocity on August based on HadGEM2-ES (RCP4.5) in upstream: a) at maximum value of discharge, b) at mean value of discharge, c) at minimum value of discharge

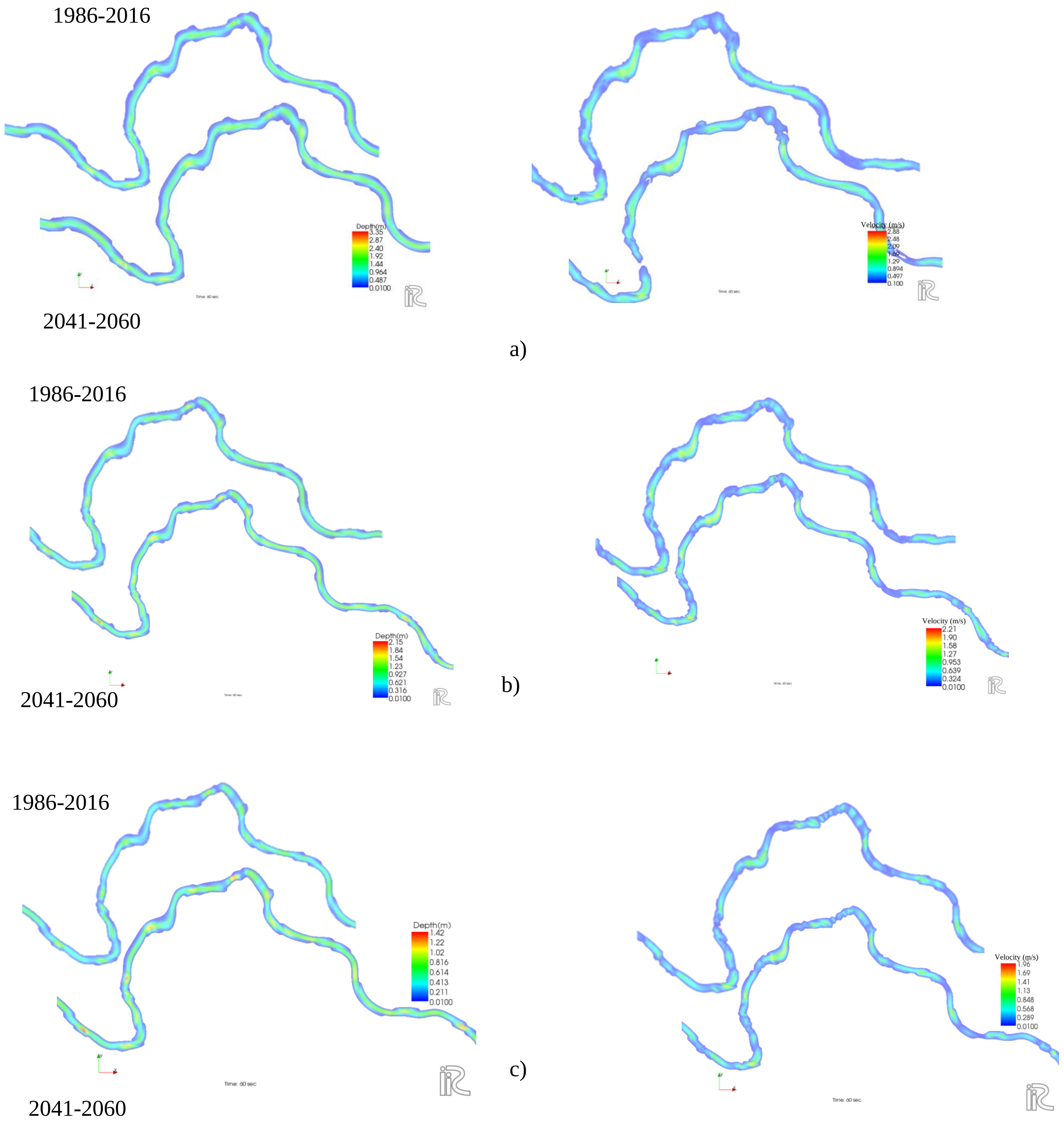


Figure 4-19 Visualized impact of climate change on water depth and velocity on August based on HadGEM2-ES (RCP4.5) in middle stream: a) at maximum value of discharge, b) at mean value of discharge, c) at minimum value of discharge

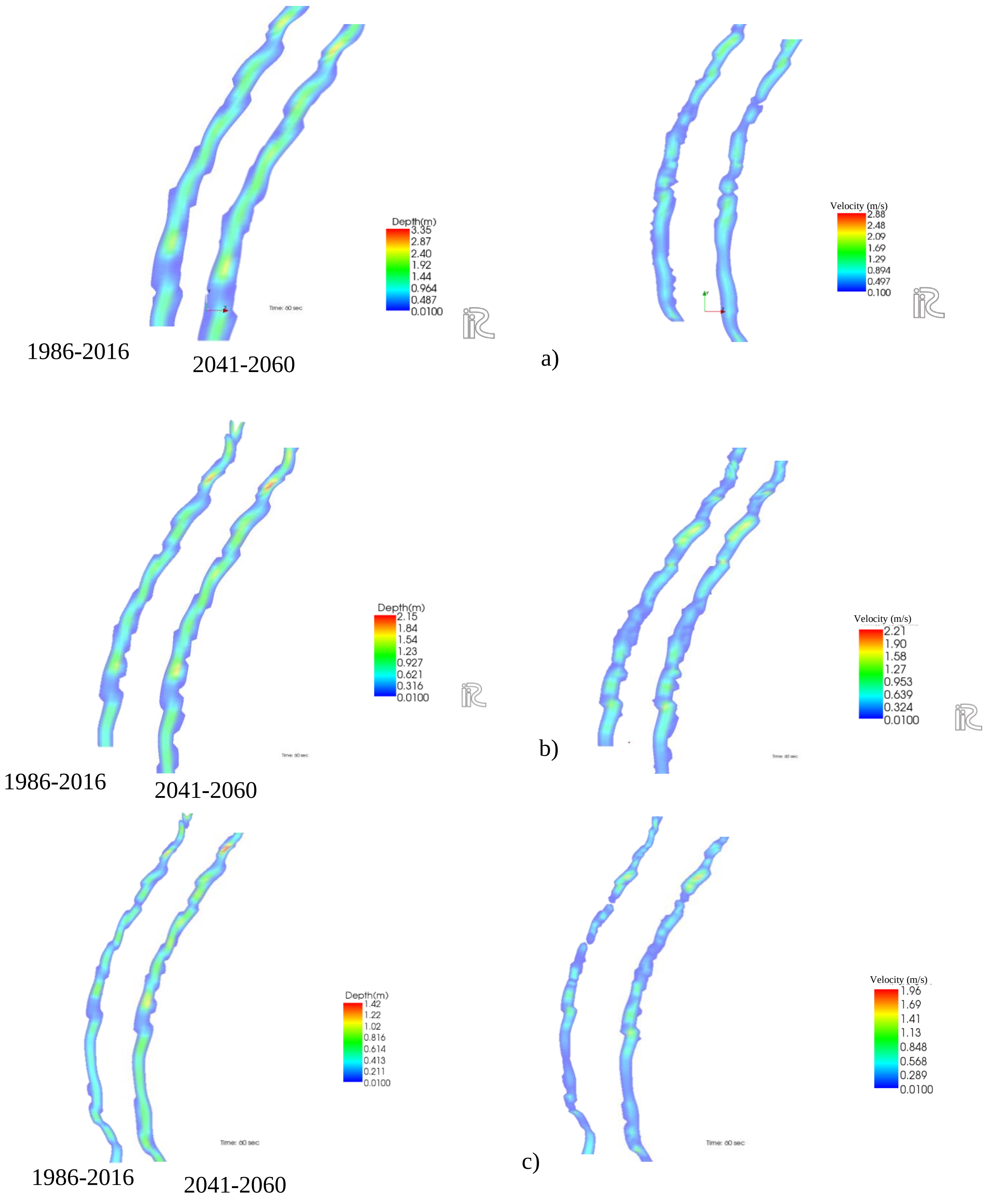


Figure 4-20 Visualized impact of climate change on water depth and velocity on August based on HadGEM2-ES (RCP4.5) in downstream: a) at maximum value of discharge, b) at mean value of discharge, c) at minimum value of discharge

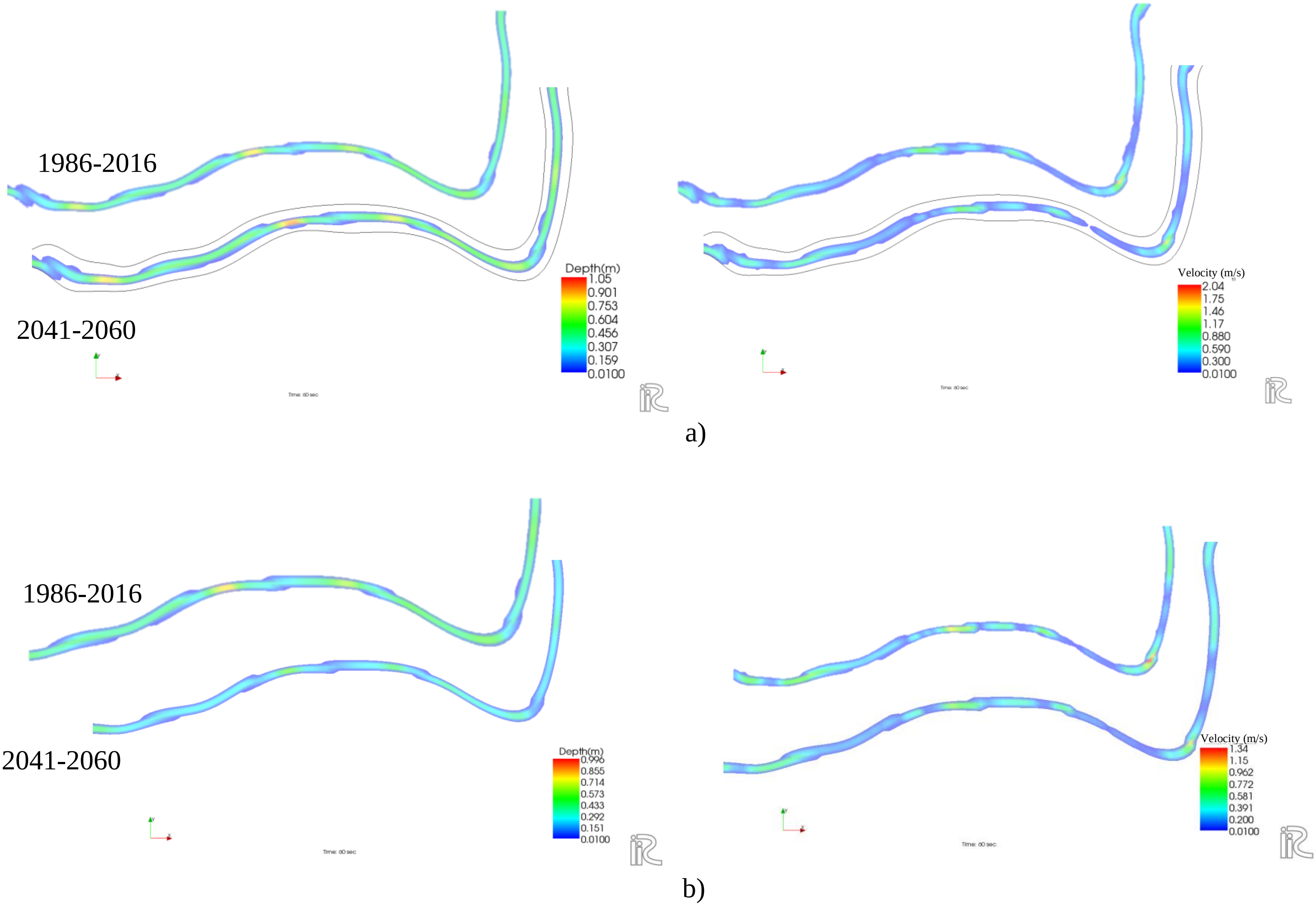


Figure 4-21 Visualized impact of climate change on water depth and velocity on January based on MICRO5 (RCP8.5) at upstream: a) at mean value of discharge, b) at minimum value of discharge

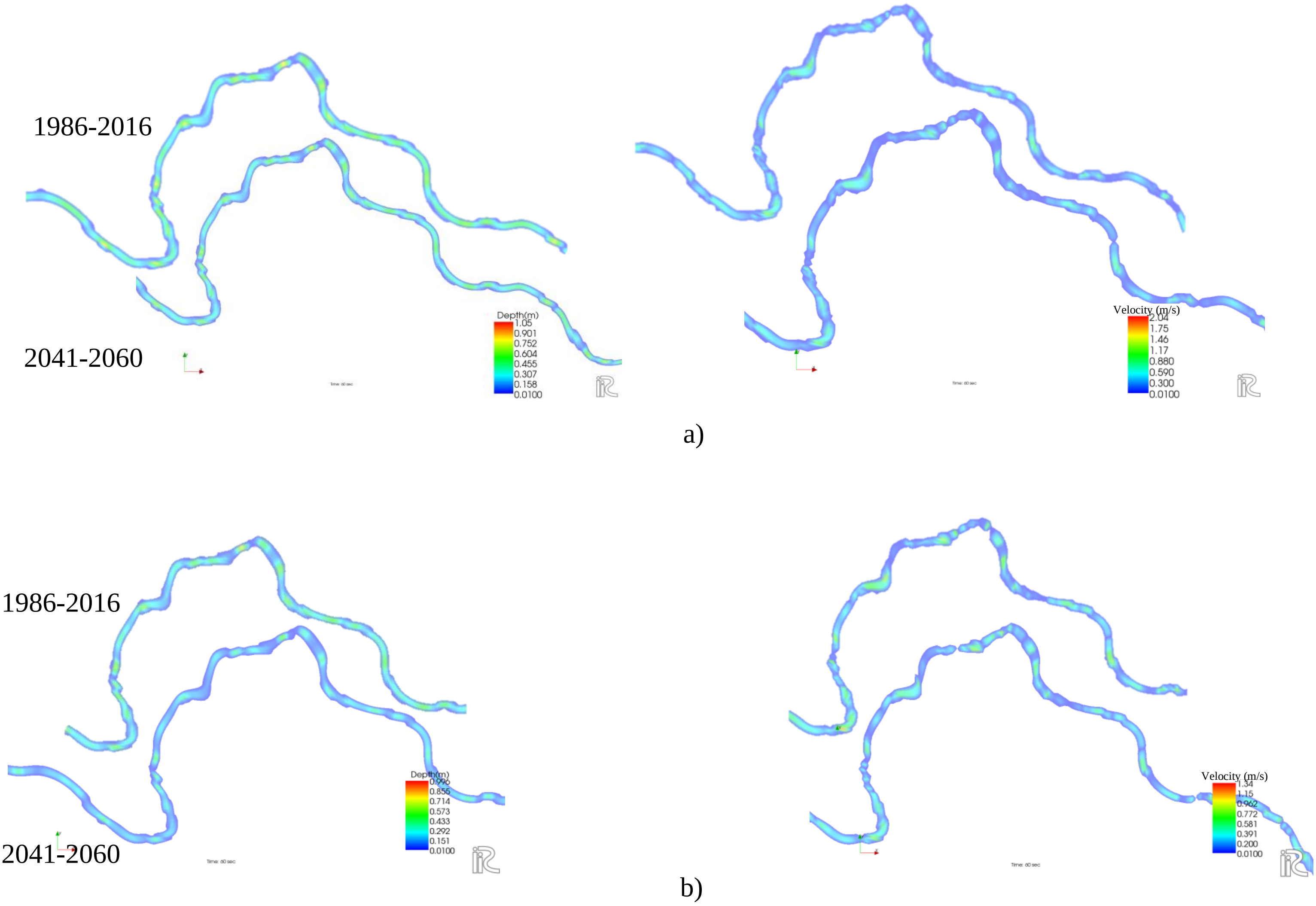


Figure 4-22 Visualized impact of climate change on water depth and velocity on January based on MICRO5 (RCP8.5) at middle stream: a) at mean value of discharge, b) at minimum value of discharge

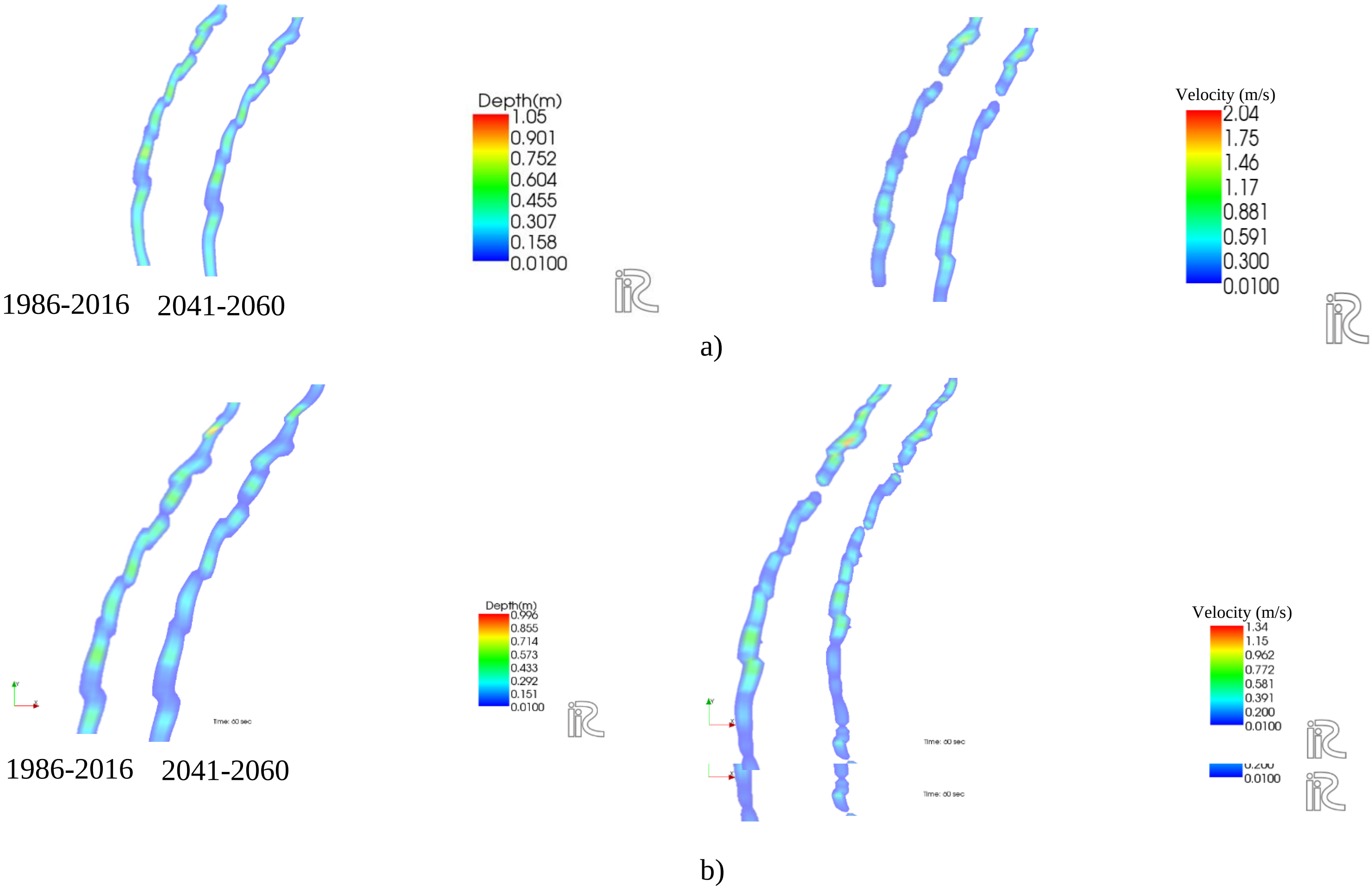
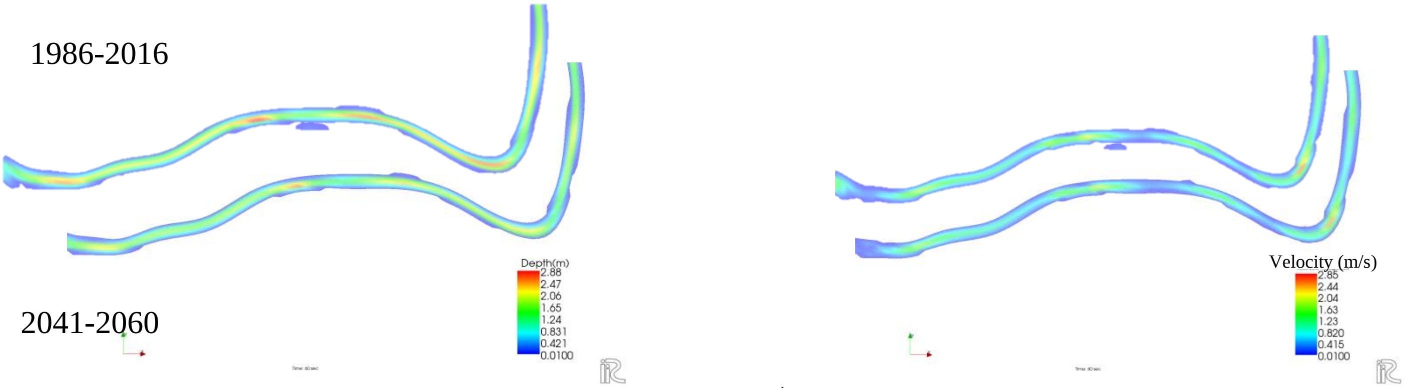
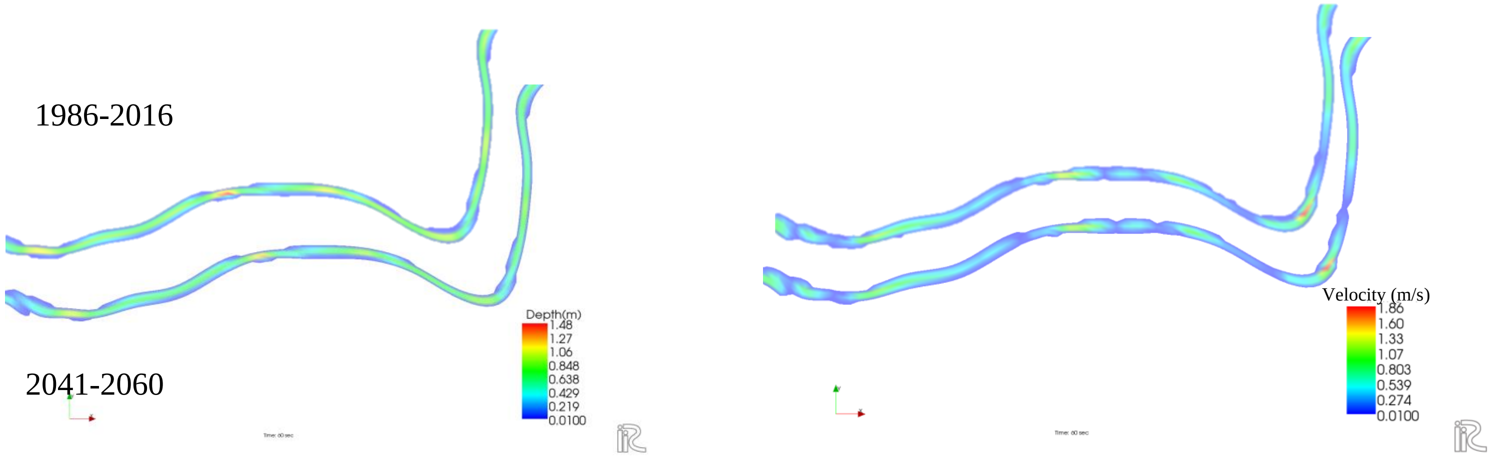


Figure 4-23 Visualized impact of climate change on water depth and velocity on January based on MICRO5 (RCP8.5) at downstream: a) at mean value of discharge, b) at minimum value of discharge



a)



b)

Figure 4-24 Visualized impact of climate change on water depth and velocity on July based on MICRO5 (RCP8.5) at upstream: a) at mean value of discharge, b) at minimum value of discharge

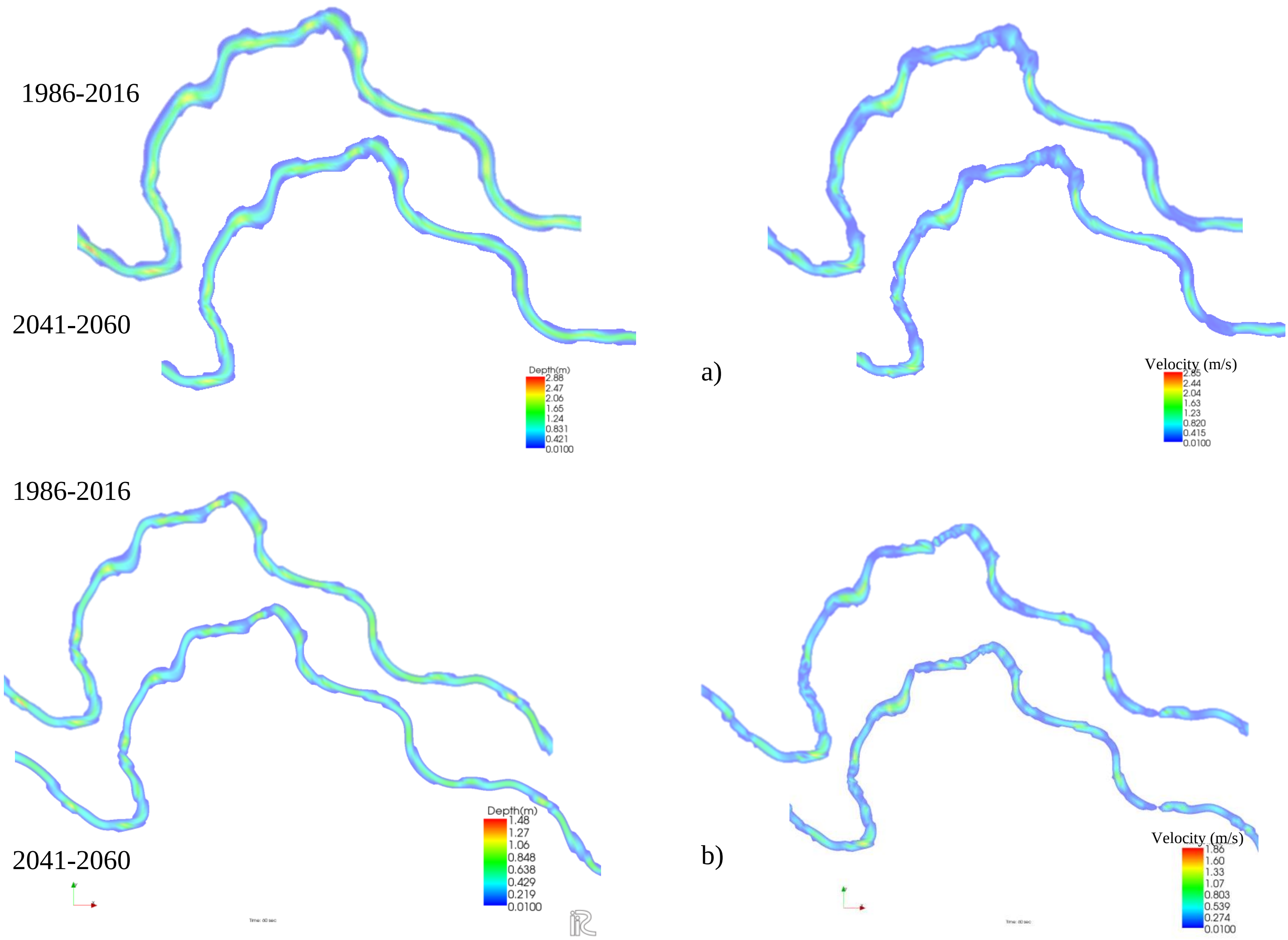


Figure 4-25 Visualizes impact of climate change on water depth and velocity on July based on MICRO5 (RCP8.5) at middle stream: a) at mean value of discharge, b) at minimum value of discharge

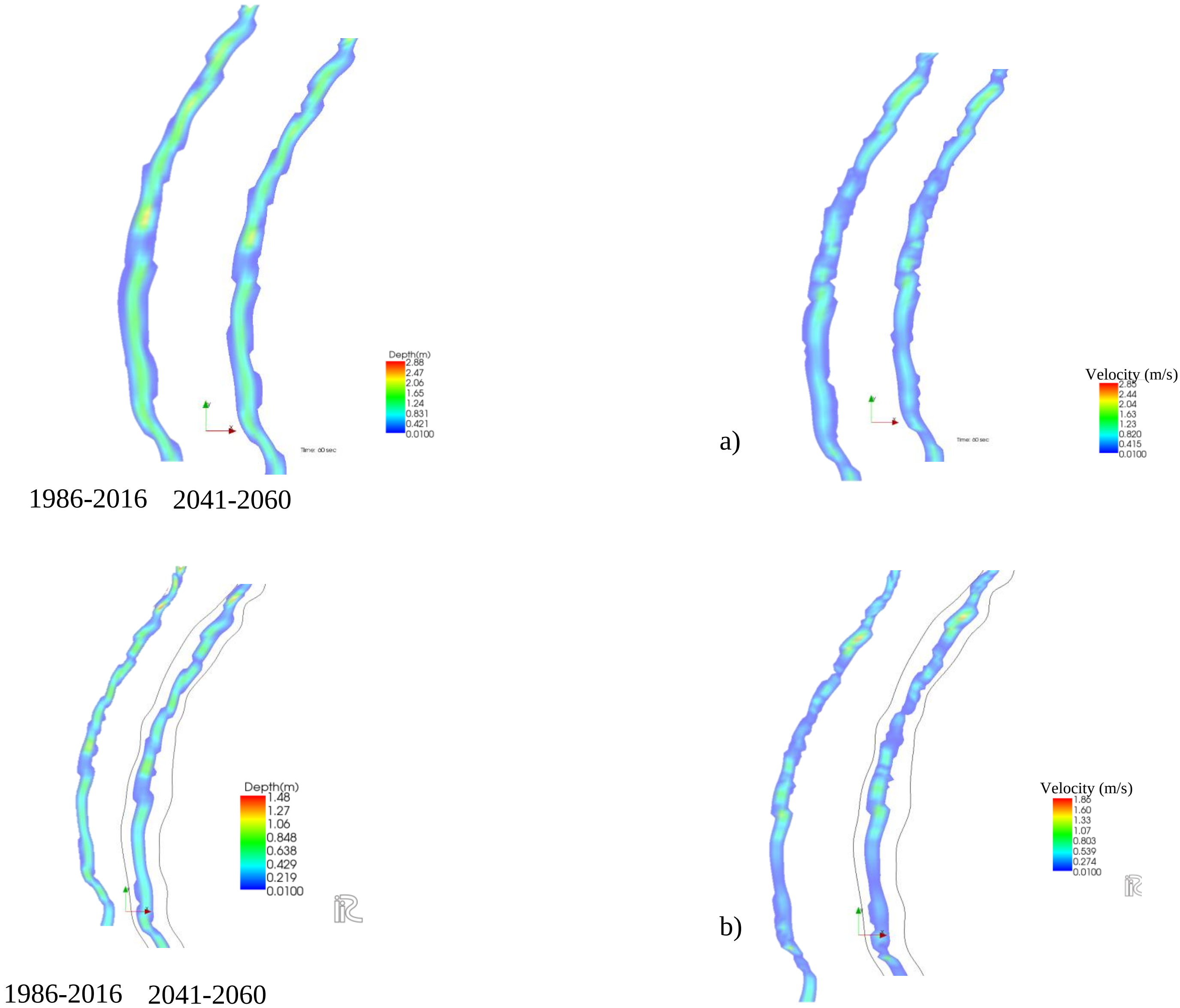


Figure 4-26 Visualized impact of climate change on water depth and velocity on July based on MICRO5 (RCP8.5) at downstream: a) at mean value of discharge, b) at minimum value of discharge

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Chapter 5: Impact assessment of climate change on habitat suitability considering water temperature

5-1. Introduction

It is about three decades, understanding cause-effect relationships between natural and human-made distresses became a challenge for scientist making them study on stream health and habitat suitability. Generalized linear models (GLM), generalized additive models (GAM), boosted regression trees, artificial neural networks, random forests, fuzzy logic-based, and Bayesian belief networks are methods used in different studies to assess the aquatic life and riverine ecosystem (1–4). On the other hand, trying to understand the ecological influence of hydraulic riverine system has provided aquatic habitat suitability models such as the physical habitat simulation model (PHABSIM) to analyze quantitatively describing the relationships between species and habitat considering hydrology parameters and ecology attributes. However, there are some points about PHABSIM which are criticizing this model, for example; it is based on expert knowledge and ignoring the interaction of habitat variables. So other habitat models such as CASiMiR which is based on fuzzy logic were developed (5). To make species distribution models and maps, CLIMEX and MaxEnt are two most widely used softwares which can predict species distribution in current and future conditions. CLIMEX uses climatic suitability predictions of a specific region for target species, while; various environmental variables with presence-only data are used by MaxEnt to model species distribution (6–8). Several studies are using the River2D model to preserve biodiversity and to manage water resources (9) which is also as a solver in iRIC (International River Interface Cooperative) software. This software has 17 solvers some of which are widely used for hydrological aims in recent years, especially models of Nays2DH, River2D,and FaSTMECH (10–12). Among different solvers of iRIC software, EvaTRiP (Evaluation Tools for River environmental Planning) is unique solver in which the necessity of river bank protection as well as the region of fish habitat is being evaluated. There are short definition of each of these models (3,5):

5-1-1. Habitat modeling

- *Generalized linear models (GLM)*

A generalized linear method is a kind of the common linear model which can process response variables in a non-normal distribution. As a result of several families of probability distributions available, such as the Binomial and Poisson, GLM is known as a flexible Method for habitat suitability calculations. The general form of GLM is using the same notations used for multiple linear regressions:

$$g(E(Y))=\beta_0 + X^T\beta \quad (5\text{-}1)$$

Where $X = (x_1, \ldots x_m);\beta=(\beta_1 ,\ldots, \beta_m)$; g: link function.

- *Generalized addictive method (GAM)*

A generalized addictive method (GAM), instead of using a parametric pre-establishing model, builds a model using smoothing functions to test the response curve if it is bell-shaped or not. Then it will compare the additive effect of each explanatory variable from its response curves in the prediction, directly. The general form of GAM equation is as below:

$$g(E(Y)) = \beta_0+f_1(x_1)+\ldots f_m(x_m) \quad (5\text{-}2)$$

where f is smoothing function.

As the ecological data often follow the non-normality distribution (variability is not constant in different conditions), the GAMs consist of several exponential families to fit various response distributions. So that it allows dealing with high non-linear and non-monotonic response curves.

- *Boosted regression trees*

Boosted regression trees (BRT) approach differs fundamentally from traditional regression methods. This method produces the technique of boosting to combine large numbers of relatively simple tree models, instead of using a single 'best' model. BRT aims to improve the performance of a single model. In this regards it fits many models and combining them for prediction by using two algorithms (13):

a) Regression trees are from the classification and regression tree (decision tree) group of models,

b) Boosting builds and combines a collection of models.

- *Random Forest*

Boosting has features that differentiate it from other model aggregation methods. Random forest (RF) is one of them which is bootstrap aggregation and is so popular (13). RF is a model including a combination of tree predictors in which each tree has been made by the values of a random vector having same distribution for all trees in the forest and sampled independently (4). RF is a non-parametric method follows steps bellow to assess predicted relationship between lots of different potential predictor variables and response variables (14):

1) Recognizing a set of randomly trees selected from predictors and observations

2) Generating hundreds or thousands of random trees

3) Entering data into trees and classifying by all trees.

4) Considering a vote for each classified tree and classifying a grid square based on the majority vote among all trees

- Physical *habitat* simulation model (PHABSIM)

Trying to understand the ecological influence of hydraulic riverine system has provided aquatic habitats suitability models such as to analyze quantitatively describing the relationships between species and habitat considering hydrology parameters and ecology attributes. PHABSIM) would be useful as eco-factors indicating physical habitat is included. This model uses the suitability curve method to establish the relationship between species preference and physical habitat, which is based on expert knowledge and did not consider the interaction of habitat variables.

- *Computer Aided Simulation Model for Instream Flow Requirements (CASiMiR)*

CASiMiR is based on fuzzy logic that was developed which is the first river habitat software program considering expert knowledge and imprecise information and selecting eco-factors more flexible than suitability curve. The simulation model comprises modules with individual computing programs and by combining them a particular case in question will be prepared (15). CASiMiR is a riverine ecosystem model that is useful for simulating complex biotic–abiotic relationships. This model is popular to evaluate the effects of hydrological alterations caused by hydropower operations (16).

- *CLIMEX*

The CLIMEX software is a climate-specific tool which is being used for analyzing potential distributions of species. This model by considering climate change and predict potential distribution, seasonal phenology, and climate similarity can assess the suitability of specific regions for target species (8).

- *Maximum entropy (MaxEnt)*

Maxent (maximum entropy) is recommended whose application is based on a theory which is that when there is an unknown probability distribution, the most reasonable conclusion is the most uncertain or the most random conclusion. This matches the known knowledge which is the only unbiased choice that can be made. This model performs well with a small amount of input data and eco-factors in different categories are available for it. Moreover, MaxEnt makes it possible to apply environmental variables such as geographical factors, distance, and land cover in order to analyze the contribution of each variable. So in recent years, it has been developed rapidly(5,8).

- *River2D model*

The software River2D is a two-dimensional depth-averaged model of river hydrodynamics which can also be used for fish habitat modeling. In this regard, the habitat suitability is calculated by linking the physical parameters with the habitat requirements of selected indicator species. There are three main steps in this software (17):

1) Calculating weighted usable area (WUA).

2) Generating hydraulic rating curves (flow vs. habitat relationship) for the different key species in order to assess the habitat suitability as a function of flow rate.

3) Combining step two with a historical flow time series to produce a physical habitat time series and finally getting a physical habitat duration curve.

- *International River Interface Cooperative software (iRIC)*

This software is providing a free numerical simulation platform for solving problems related to water science and engineering. iRIC is a tool to analyze river flow and morphodynamics capable of predicting floods, rainfall runoff generation, small flows, habitat assessment and more (18). This software has 17 solvers some of which are widely used for hydrological aims in recent years, especially models of Nays2DH, River2D, and FaSTMECH (10–12). Among different solvers of iRIC software, EvaTRiP (Evaluation Tools for River Environmental Planning) is a unique solver in which the necessity of river bank protection as well as the region of fish habitat is being evaluated. In other words, an evaluation function is built by hydraulic parameters and SI values in this solver. Parameters are the value of depth, velocity plus substrate and SI value which is calculated based on each value corresponding to each parameter (i.e. depth or velocity) (19). Habitat suitability index (HIS) models representing the relationship between each relevant environmental parameter (water depth, water velocity, ….) and an associated suitability index (SI).

This index is achievable using this formula:

$$HSI = SI\ (velocity) * SI\ (Depth) * SI\ (Water\ temperature)\ * \ldots \quad (5\text{-}3)$$

WUA (Weighted Usable Area) is calculated as the sum of the area-weighted products of point HSI for the cross-section or reach, where area is that of the respective hydraulic cells. WUA is an index of habitat quality and quantity.

5-1-2. Water temperature modeling

Climate change will also influence water temperature having direct and indirect effects on the health and productivity of aquatic livings such as species distribution, juvenile survival, as well as; dissolved oxygen concentrations (20). Although warm temperatures can have positive effects on growth rates of some aquatic species, such as albalone, generally speaking; high temperatures are known as a factor in disease outbreaks. Moreover, a higher temperature will lead to a decrease in oxygen solubility, which plays an important role in both growth and mortality (21). Also, temperature not only influences growth rate, but also plays a role in determining the size of species, and is an important factor in juvenile survival (22)In recent years, analyzing water temperature besides assessing the impact of climate change on habitat suitability has made a notable challenge among hydrologists and ecologist. For example, Zhang et al, (2019) analyzed the impacts of climate change and hydropower on fish habitats considering water temperature. In their study, a water temperature model was established to simulate the water temperature. The model was coupled with the hydrological model considering groundwater, as well as seasonal and daily signals, depending on the air temperature (23). Ficklin et al. (2012) (20) developed a hydroclimatological stream temperature model within the SWAT model combining the effects of watershed hydrological conditions and air temperature. It has also been used to assess the impact of climate change on stream in other studies (24).

In this study, habitat suitability for *Zacco platypus* (Oikawa) species and *Zacco temminckii* (Kawamutsu) fish were analyzed by using EvaTrip solver of iRIC. I chose working with this model as using this solver for projecting future habitat suitability is for the first time, moreover; suitability indexes of target fish are available in the sample data of this solver. This habitat suitability analyses have been done for three different parts of the Kikuchi river mentioned in the previous chapter (upstream, middle stream and downstream).

In addition, the water temperature was simulated for future periods using a modified SWAT model water temperature formula to have a better vision on habitat suitability by 2080.Method

5-1-3. EvaTrip

In this paper, two solvers of the iRIC model were used to calculate HSI for the three species. In other words, the output of Nays2DH solver was used to run EvaTrip solver. In order to simulate horizontal two-dimensional (2D) flow, Nays2DH was developed which is also modeling sediment transport, and morphological changes of bed and banks in rivers. After running this solver and getting results about river characteristics including water velocity and water depth, its output should be used as input for EvaTrip solver. This solver has two main steps to evaluate habitat suitability in each cell of the river grid. First, it calculates the physical index of discharge, depth, and river channel coefficients. Next, a fitness index (SI) will introduce with a value of 0 to 1 based on the distribution condition or observed data indicating the degree of selection of the physical index(Figure 5-1) (19):

f [h(k) ≤ hi,j ≤ h(k+1)] then

$$SI\,(i,j) = SI(k) + \frac{SI(k+1) - SI(k)}{h(k+1) - h(k)}\,[h_{i,j} - h(k)] \quad (5\text{-}4)$$

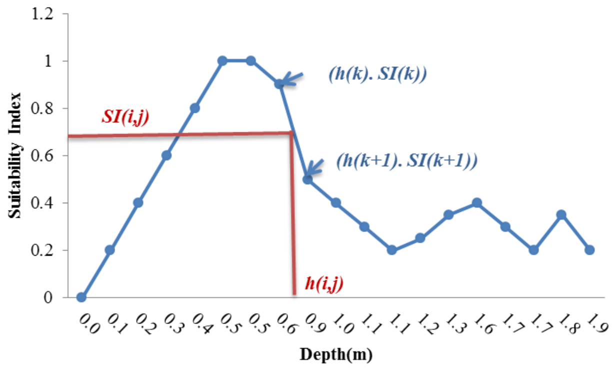


Figure 5-1. Explanation of how EvaTrip finds SI for different points of river put in EvaTrip manual.

Where (k) is the number of a certain point in the data and h (k) is value of hydraulic variable such as water depth and SI (k) is suitability index for the point of (k). Using a linear interpolation, it is possible to have HIS for each cells of river grid (Figure 5-2). It is notable that most parts of EvaTrip solver's formula is mostly following PHABSIM method to find out

HIS (19). Moreover, there is some sample data about SIs of target fish species in Japan used in this study.

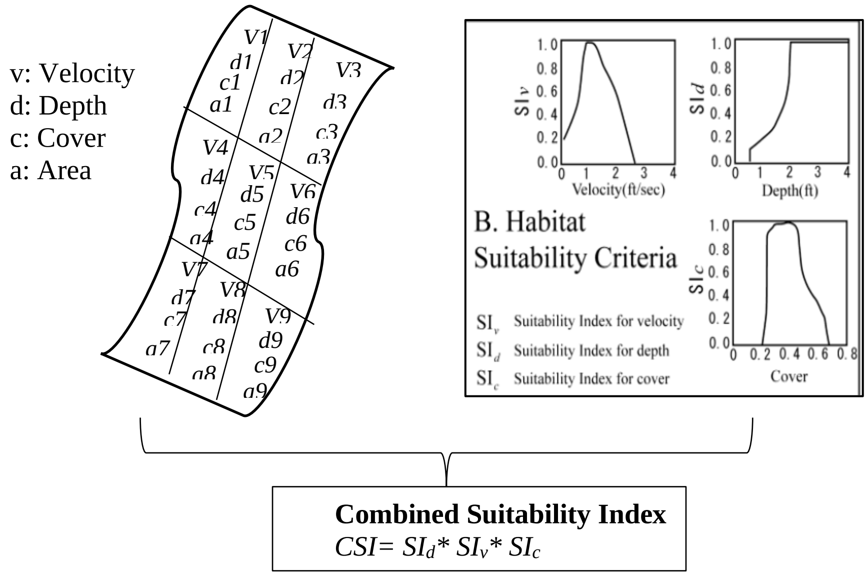


Figure 5-2. EvaTrip calculation method mentioned in EvaTrip manual

Based on available sample data in EvaTrip solver, SIs for two target fish were used.

After determining HIS by EvaTrip, WUA was obtained by summing all products of the area of each mesh cell and their HSI values in GIS environment. This parameter computed within the reach at a specific discharge as follows:

$$\text{WUA} = \sum_{n}^{i} HSI_i * A_i \qquad (5\text{-}5)$$

Where, HSI_i is the HSI value of cell i, A_i is the surface area of cell i.

5-1-4. Water Temperature

It is important to know how changes in future climate and water temperature might affect the population and distribution of species in aquatic environments (25). The default formula in SWAT model is as follow (26):

$$T_{water} = 5.0 + 0.75 * \overline{T}_{air} \qquad (5\text{-}6)$$

Where T_{water} is the average water temperature for the day (°C) and $\overline{T}air$ is the average air temperature on the day (°C). However, it should be considered that in addition to air temperature, other factors such as snowmelt, surface runoff, and groundwater are also influencing water temperature. So by changing the SWAT model default formula the impacts of these factors took into account in order to calculate water temperature for the case study. In this regards three different steps have been passed including calculation of (20,27):

1) Local water temperature

$$T_{w,local} = \frac{(T_{snow}\ \text{sub\_snow}) + (T_{gw}\ \text{sub\_gw}) + (\lambda T_{air,lag})(\text{sub\_surq} + \text{sub\_latq})}{\text{sub\_wyld}} \quad (5\text{-}7)$$

Where sub_snow is the snowmelt runoff contribution to streamflow within the subbasin (m^3/d), sub_gw is the groundwater flow contribution to streamflow within the subbasin (m^3/ d), sub_surq is the surface runoff contribution to streamflow within the subbasin (m^3/d), sub_latq is the soil lateral flow contribution to streamflow within the subbasin (m^3/d), sub_wyld is the total water yield contribution to streamflow within the subbasin (m^3/d).

T_{snow} is the temperature of snowmelt runoff (0.1 °C), T_{gw} is the groundwater flow temperature (°C), T_{air}, lag is the average daily air temperature with a lag (°C), and λ is a calibration coefficient. The lag (days) is a parameter incorporated to allow the effects of delayed surface runoff and soil water flow into the stream. λ is a calibration coefficient denoting the relationship between T_{air}, lag, surface runoff and lateral flow.

2) Initial stream temperature

$$T_{w,initial} = \frac{T_{w,up}(Q_{outlet} - \text{sub\_wyld}) + T_{w,local}(\text{sub\_wyld})}{Q_{outlet}} \quad (5\text{-}8)$$

Where $T_{w,up}$ is the temperature of the streamflow entering the subbasin from the upstream subbasin (°C) and Q_{outlet} is the streamflow discharge at the outlet of the subbasin. In the case of headwater streams without inflow, Tw, up = Tw, initial.

3) Final stream temperature

$$T_w = T_{w,\ initial} + (T_{air} - T_{w,\ initial}).\ K.\ TT \qquad \text{if}\ \ Tair > 0 \quad (5\text{-}9)$$

$$T_w = T_{w,\ initial} + [(T_{air} + \varepsilon) - T_{w,\ initial}).\ K.\ TT \qquad \text{if}\ \ Tair \leq 0 \quad (5\text{-}10)$$

Where Tair is the average daily temperature, K (h-1) is a bulk coefficient of the heat transfer and ranges from 0 to 1, TT is the water travel time in the stream (h) and ε is air temperature addition coefficient, which is included to account for water temperature pulses when the air temperature is below 0 °C.

sub_snow, sub_gw, sub_surq, sub_latq, and sub_wyld are available in the SWAT model (20). Tgw is often 1–2°C higher than mean annual air temperature of a region (28). In order to calibrate the model, K and λ are useful coefficients whose default value is 1(27).

Using these information, water temperature data from 7 station (Figure 5-3) was collected in order to calibrate and validate the model. Table 5-1 illustrates water temperature stations in the Kikuchi river basin.

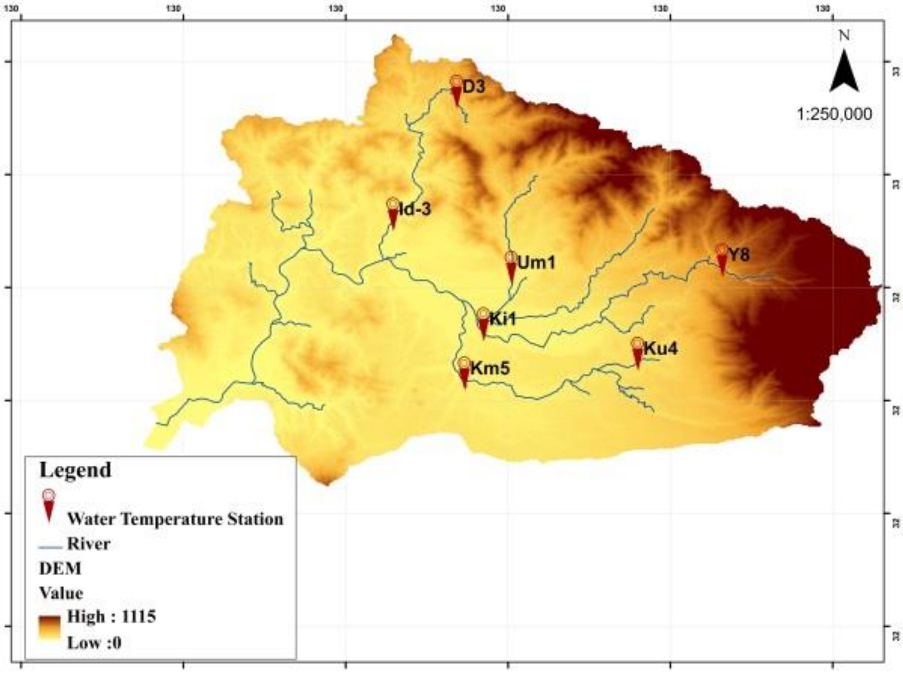


Figure 5-3. Water temperature stations on the rivers in Kikuchi basin

Table 5-1. Information of water temperature stations on the rivers in Kikuchi basin

Station	Latitude	Longitude	Elevation	Annual water temperature C°
D3	33° 7' 34.864" N	130° 43' 23.707" E	140	13.74
Id-3	33° 2' 32.171" N	130° 40' 46.865" E	21	15.48
Um1	33° 0' 20.196" N	130° 45' 38.556" E	41	16.54
Ki1	32° 58' 0.566" N	130° 44' 29.998" E	24	16.09
Km5	32° 55' 58.88" N	130° 43' 42.852" E	29	17.84
Y8	33° 0' 39.110" N	130° 54' 19.105" E	310	13.98
Ku4	32° 56' 47.8" N	130° 50' 50.604" E	94	15.68

5-2. Results and Discussion

5-2-1. Water Temperature

The new stream temperature model was manually calibrated for each of the seven stations located in different sub-basins. K and λ were the most sensitive parameters and were manipulated (Table 5-2).

Table 5-2 Calibration Parameters of the New Stream Temperature Model for the Study Sites

Station	Julian Day			
	from	**to**	**λ**	**K (1/h)**
D3	1	94	1.25	0
	94	308	0.75	0
	309	366	1	0
Id-3	1	62	1.5	0
	63	307	1	0.25
	308	337	1	0
	338	366	1.5	0
Um1	1	93	1.5	0
	94	337	1	0
	338	366	1.5	0
Ki1	1	31	2	0
	32	62	2.5	0
	63	93	1.5	0
	94	123	1	0
	124	277	0.85	0
	278	338	1	0
	339	366	2	0
Km5	1	62	2	0
	63	93	1.5	0
	94	123	1.25	0
	124	154	1.5	0
	155	276	1	0
	277	337	1.25	0
	338	366	2	0
Y8	1	63	2	0
	64	94	1.25	0
	95	123	0.85	0
	125	154	0.7	0
	155	184	1.25	0
	185	277	0.5	0
	278	366	0.85	0
Ku4	1	62	2	0
	63	93	1.25	0
	94	123	1	0
	124	276	0.85	0
	277	337	1	0
	338	366	1.75	0

In this study, calibration period is July 2015 to June 2016 and validation period is August 2016 (Table 5-3). The results of calibration and validation is satisfactory as NS>0.5 and R2>0.5, PBIAS < ±10, and RMSE is less than 3 °C in most of the stations (31–33).

Table 5-3 Calibration and Validation Statistics for New SWAT Stream Temperature Model for the Study Sites

Station	**Calibration (7/2015 – 6/2016)**				**Validation (8/2016)**			
	NES	**R2**	**PBIAS (%)**	**RMSE (°C)**	**NES**	**R2**	**PBIAS (%)**	**RMSE (°C)**
D3	0.5	0.6	-5.6	2.7	0.77	0.2	-1.9	2.02
Id-3	0.6	0.6	-2.02	3	0.5	0.5	1.8	2.2
Um1	0.65	0.67	1.2	3	0.4	0.4	2.7	2.4
Ki1	0.25	0.5	-7.2	3.4	0.86	0.2	3.3	2.24
Km5	0.55	0.62	-1	3.5	0.25	0.55	-1.09	2.2
Y8	0.7	0.7	-0.1	3	0.33	0.84	-1.5	2.24
Ku4	0.35	0.5	-5.4	3.3	0.7	0.3	0.6	1.8

Based on the results, monthly water temperature is increasing 1-3 °C in the high elevation station like D3 and 1-5 °C in the low elevation station like Km5 under different RCPs by 2080 (Figure 5-17 to Figure 5-22). Moreover, the highest changes are for the station Km5 under HadGEM2-ES (RCP8.5) which has 4-6 °C increase during a year by 2080 (Table 5-12). The lowest changes are expected for station Y8 located on the Kikuchi river especially for the period of 2021-2040 under MICRO5 (RCP4.5). Monthly changes for this station are predicted to be about 0-2 °C (Table 5-13).

5-2-2. Impact of climate change on habitat suitability

Results from chapter three illustrated because of uncertainties in GCMs, expectations of the river flow for the future would be different. The highest reduction and rise are related to MICRO5 under RCP8.5 (from 46 m3/s to 41m3/s) and HadGEM2-ES under RCP4.5 (from 46 m3/s to 48 m3/s) on 2041-2060, respectively. So, in this chapter, I analyzed how average and minimum river flow will affect habitat suitability in August, January, and July for two target fish. The months of August and January were chosen to study as they are represented for the time when the river flow is in its maximum and minimum value, respectively. Moreover, the moth of July was chosen as this month is the most important time for spawning (29,30). Notably, habitat simulations have been also done for flood period and all of these simulations have been compared with and without considering water temperature. In other words, after analyzing habitat suitability by using EvaTrip based on hydraulic parameters, the impact of climate change on water temperature by using the SWAT model has been done. So that it was possible to have a wider vision about habitat suitability for Oikawa and Kawamutsu fish.

- *Oikawa*

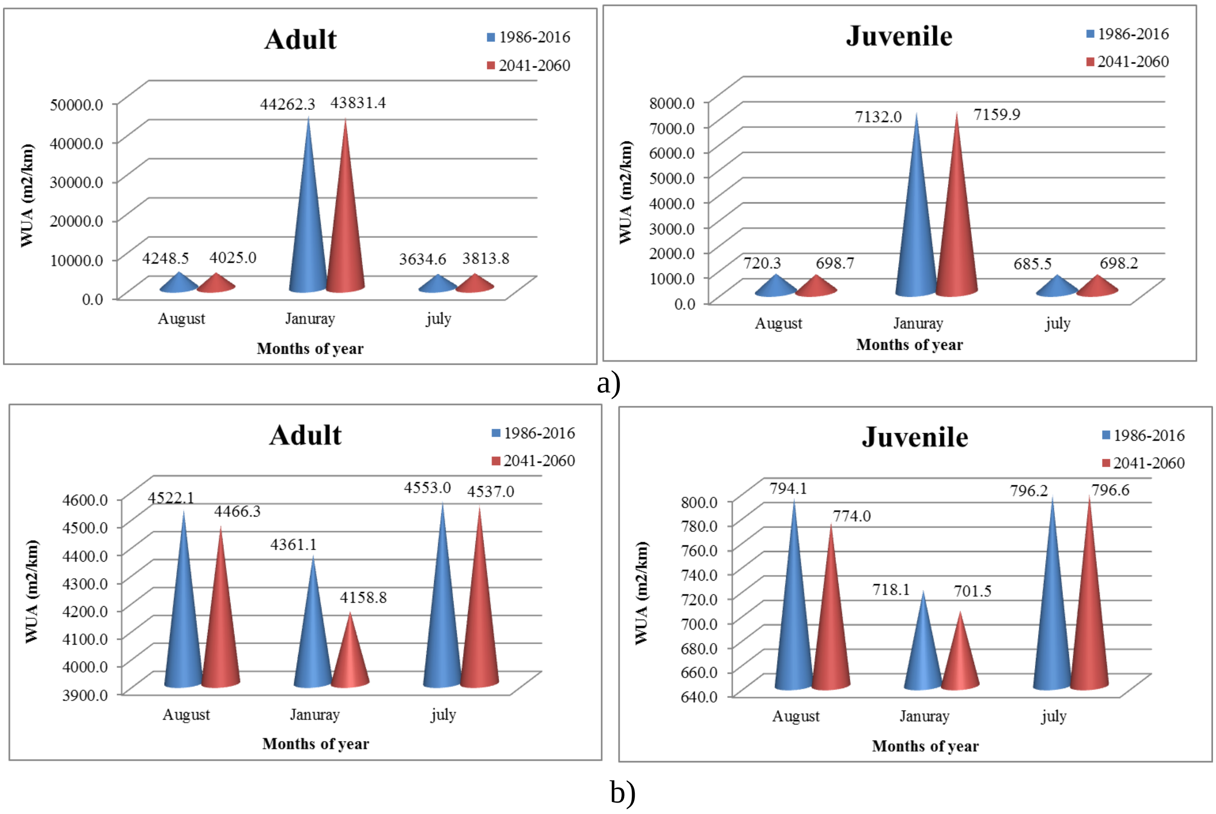


Figure 5-4 Weighted Usable Arae for Oikawa fish in different months without considering water temperature: a) average discharge of the river in the month, b) minimum discharge of the month

As it is shown in Figure 5-4 the highest values of WUA are related to the minimum discharge of the river, however; the average discharge of the river in January also makes a relatively suitable condition for Oikawa fish without any sensible changes by 2060 (Figure 5-5).

Generally, WUA is expected to decrease at the minimum value of the river flow in January and August, while; this parameter will be approximately the same for other studied conditions.

The reduction of HSI in August is mostly because of an increase in water depth and water velocity which is affecting WUA in the future. Based on our result habitat suitability of Oikawa fish will reduce this month in the adult stage and it will not find suitable habitat in the juvenile stage by 2061(Figure 5-6).

The notable point is that, although WUA is supposed to decrease in January for both life stages of the adult and the juvenile in the minimum value of river flow, HSIs in these conditions are expected to have a slight increase. Figure 5-7 and Figure 5-8 show that the reason for this result is because of losing some part of the river in the future. In other words, some parts of the river will not have water so that the Oikawa will not have those areas or the river wide will be narrower, however; in other parts of the river HSI will increase as water depth and water velocity are decreasing.

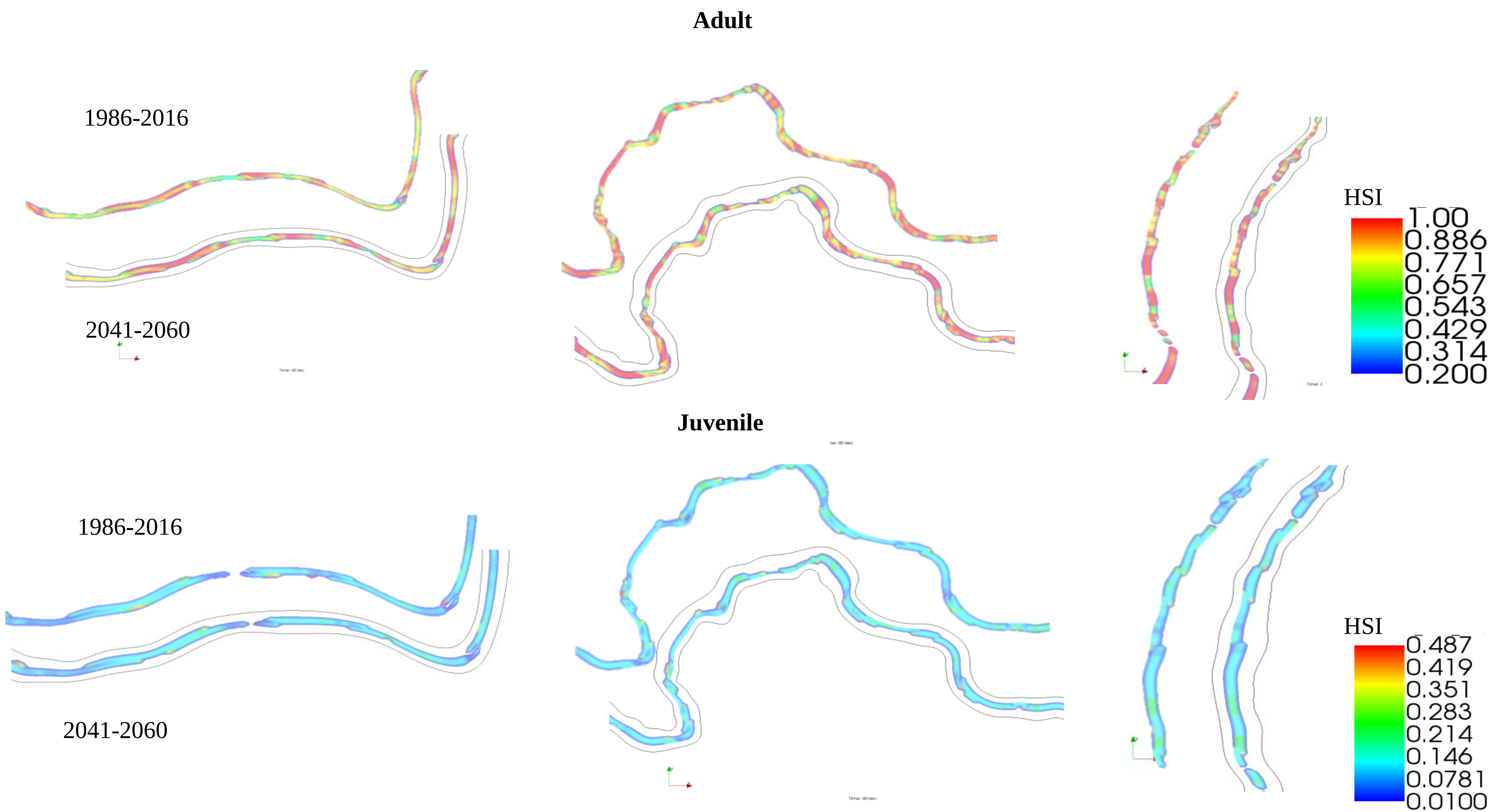


Figure 5-5 HSI for Oikawa fish at average value of discharge on January

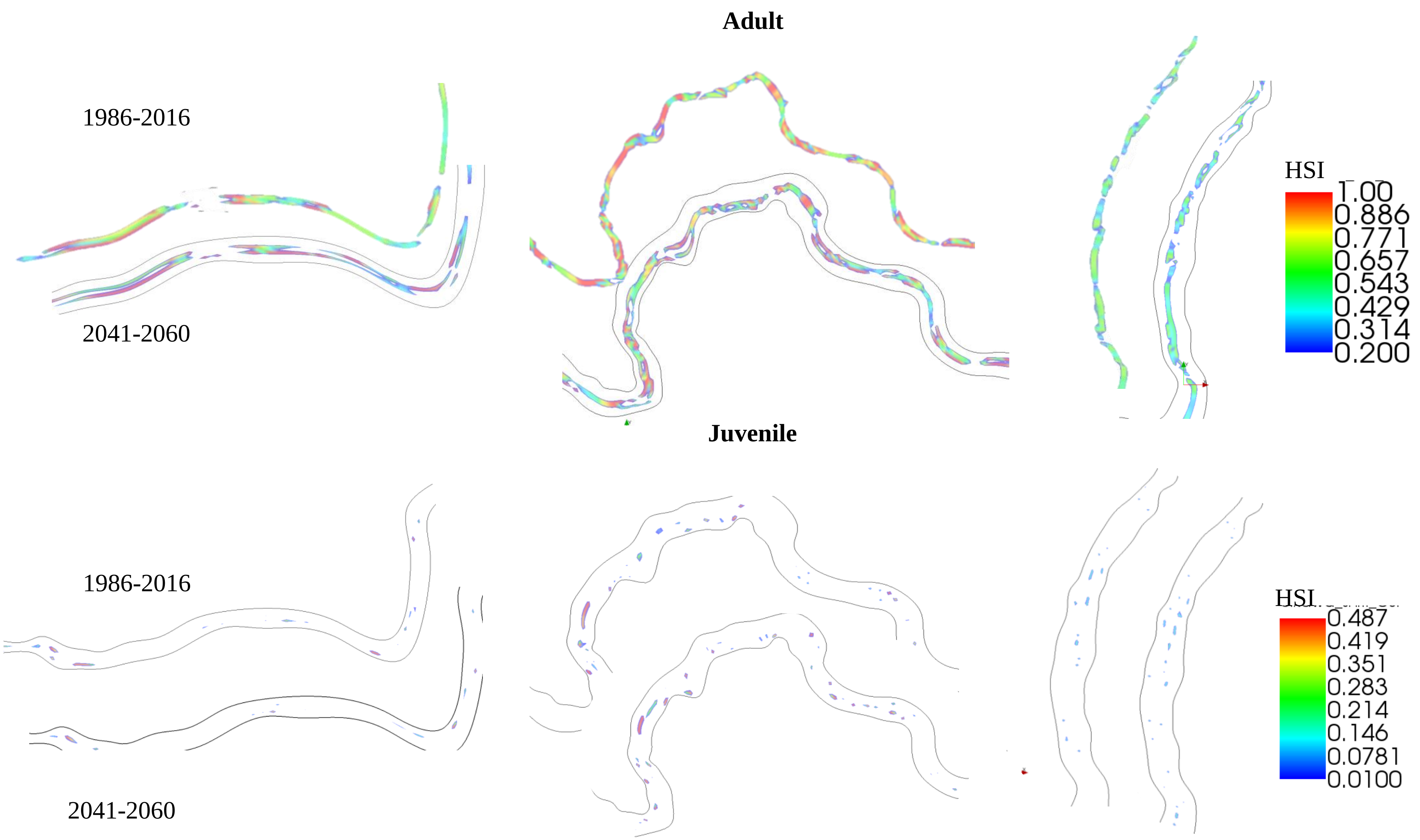


Figure 5-6 HSI for Oikawa fish at minimum value of discharge on August

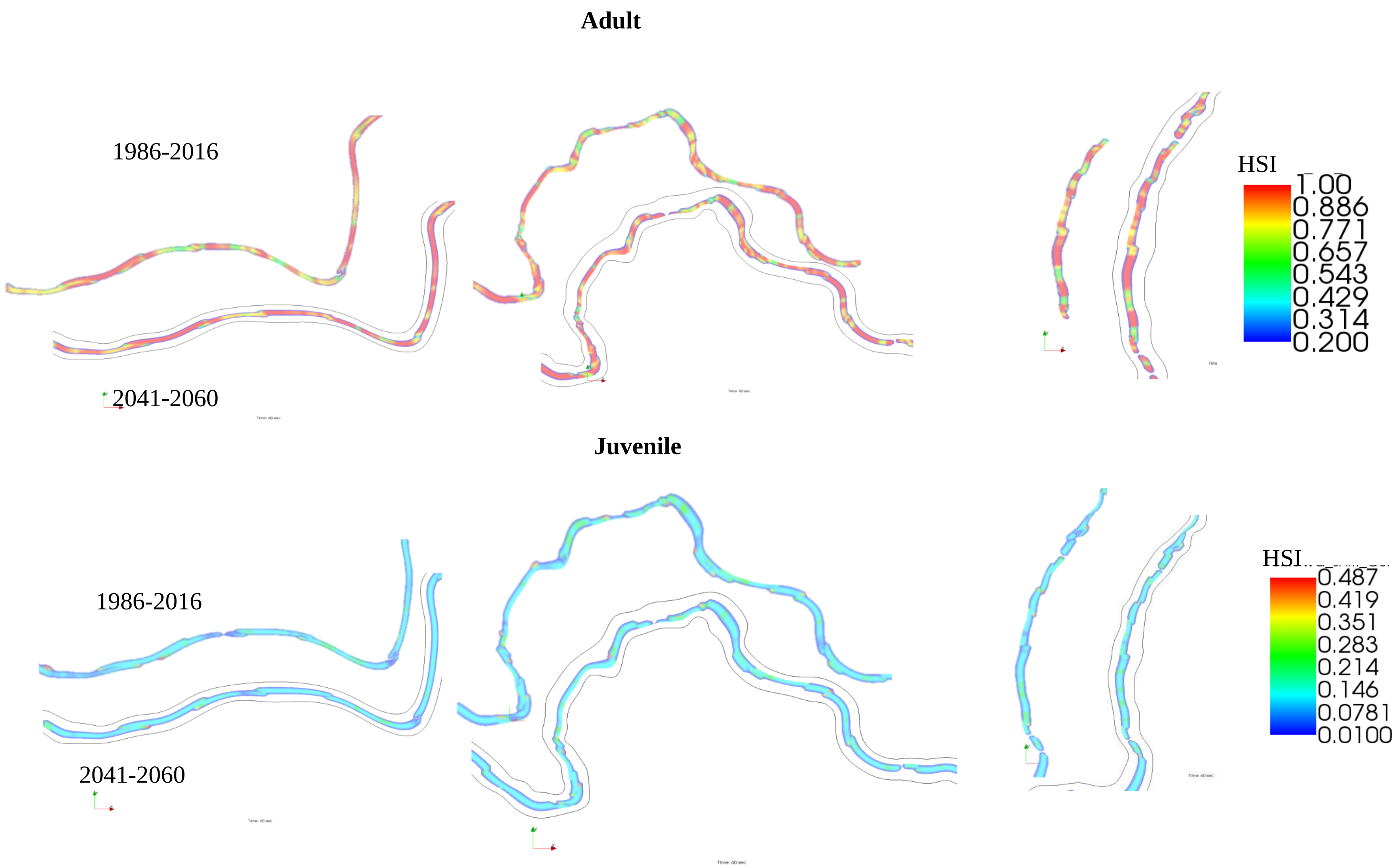


Figure 5-7 HSI for Oikawa fish at minimum value of discharge on January

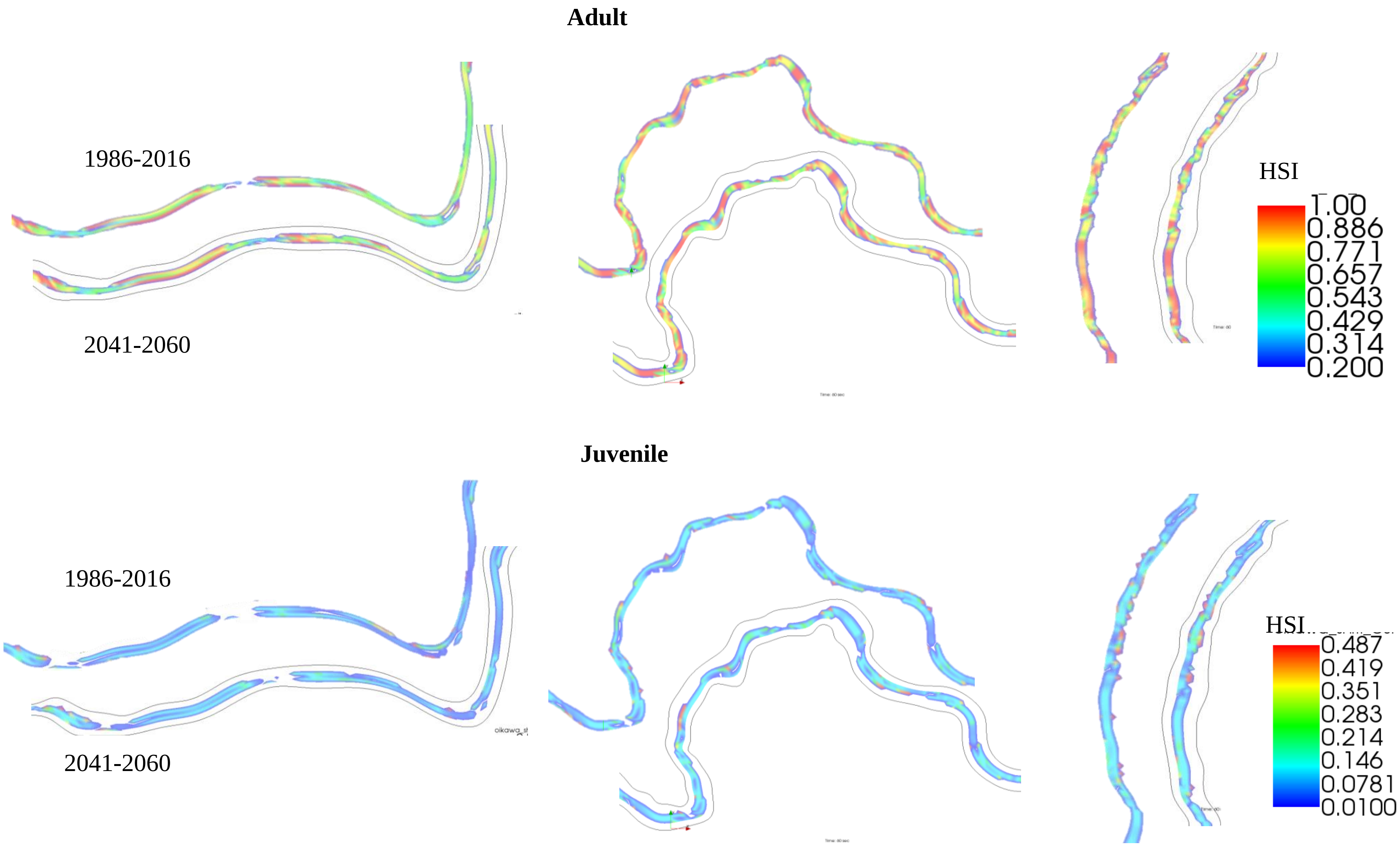
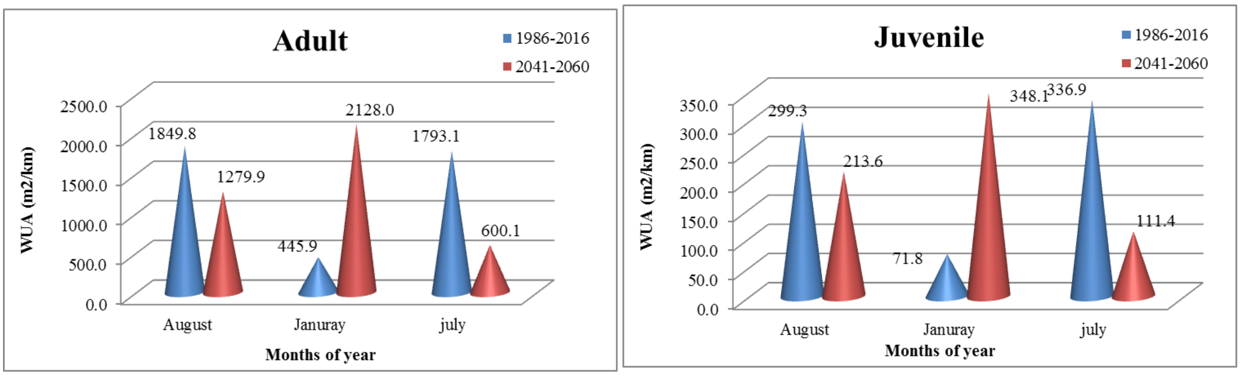
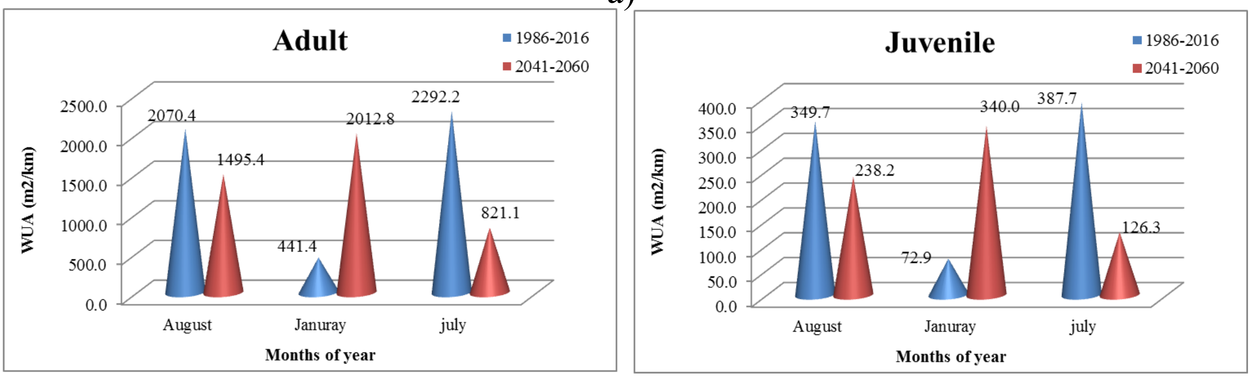


Figure 5-8 HIS for Oikawa fish at minimum value of discharge on July

As the result showed, except for January in the minimum value of discharge, WUA has no notable changes. Then, for the next step water temperature, SI for calculating WUA was considered to see to what extent this parameter can affect habitat suitability of target fish. Based on Figure 5-9, the reduction of habitat suitability in August and July is visible. The interesting point is that habitat suitability was predicted to decrease in January when only hydraulic parameters were used in WUA calculations, however; considering water temperature habitat suitability is expected to increase in this month.



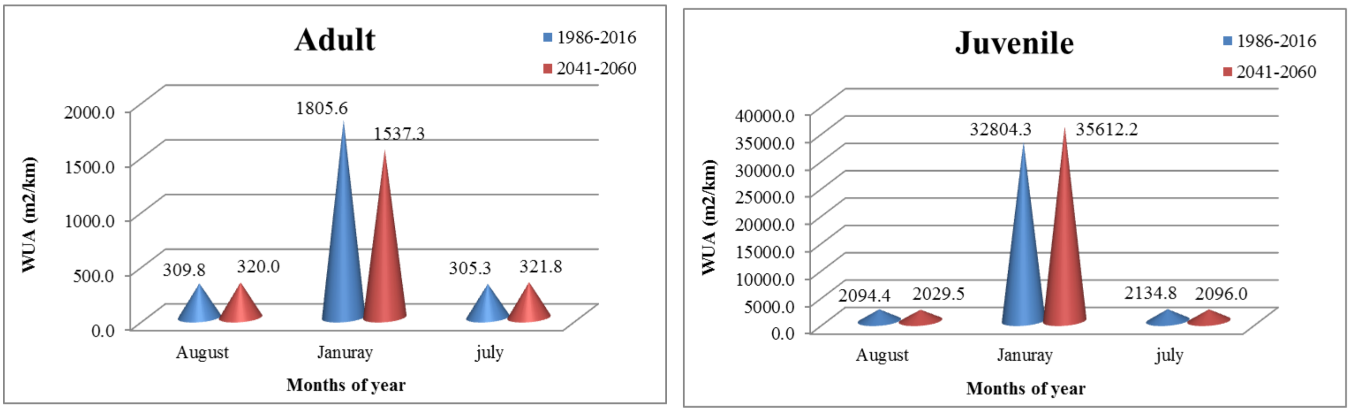
a)



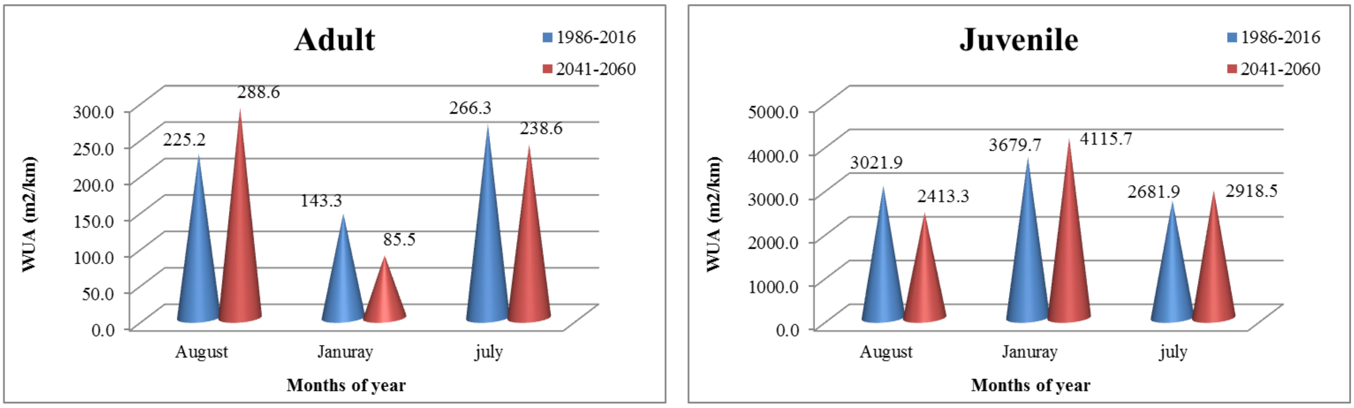
b)

Figure 5-9 Weighted Usable Arae for Oikawa fish in different months with considering water temperature: a) average discharge of the river in the month, b) minimum discharge of the month

- *Kawamutsu*



a)



b)

Figure 5-10 Weighted Usable Arae for Kawamutsu fish in different months without considering water temperature: a) average discharge of the river in the month, b) minimum discharge of the month

As it is shown in Figure 5-10 the highest values of WUA are in January, however; this parameter is also high in August and July when Kawamutsu fish in its juvenile life stage at the um value of discharge.

Generally, WUA is expected to decrease at the adult life stage, while; this parameter will increase at the juvenile stage except in August when the discharge of the river is low.

Based on our result habitat suitability of Kawamutsu fish will reduce in January at the average value of discharge in the adult stage, while; it will increase on the Juvenile stage. This is because in adult stage low water depth and velocity are not the fish preference but it is suitable at the juvenile stage (Figure 5-11). Generally, the Kikuchi river does not have high habitat suability for Kawamutsu at the adult stage in August, however; it has a better situation for juveniles even in the minimum value of discharge which is expected to decrease by 2060 (Figure 5-12). Whereas, HSI will increase at the minimum value of discharge for juveniles in

January in the future (Figure 5-13). The month of July also does not have a suitable condition for Kawamutsu, except for juveniles at the minimum value of river flow which is supposed to have a slight increase by 2060 (Figure 5-14).

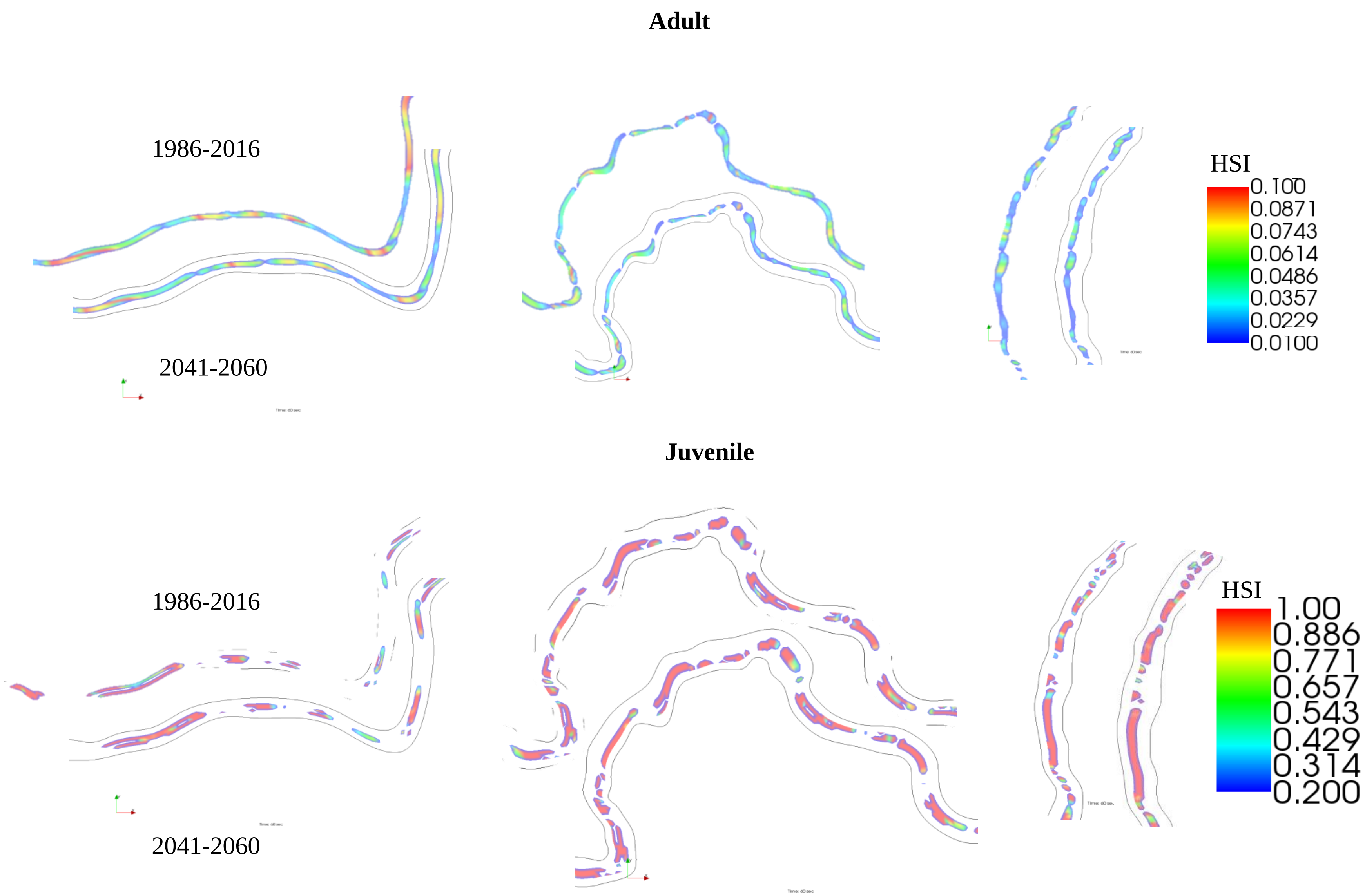


Figure 5-11 HSI for Kawamutsu fish at average value of discharge on January

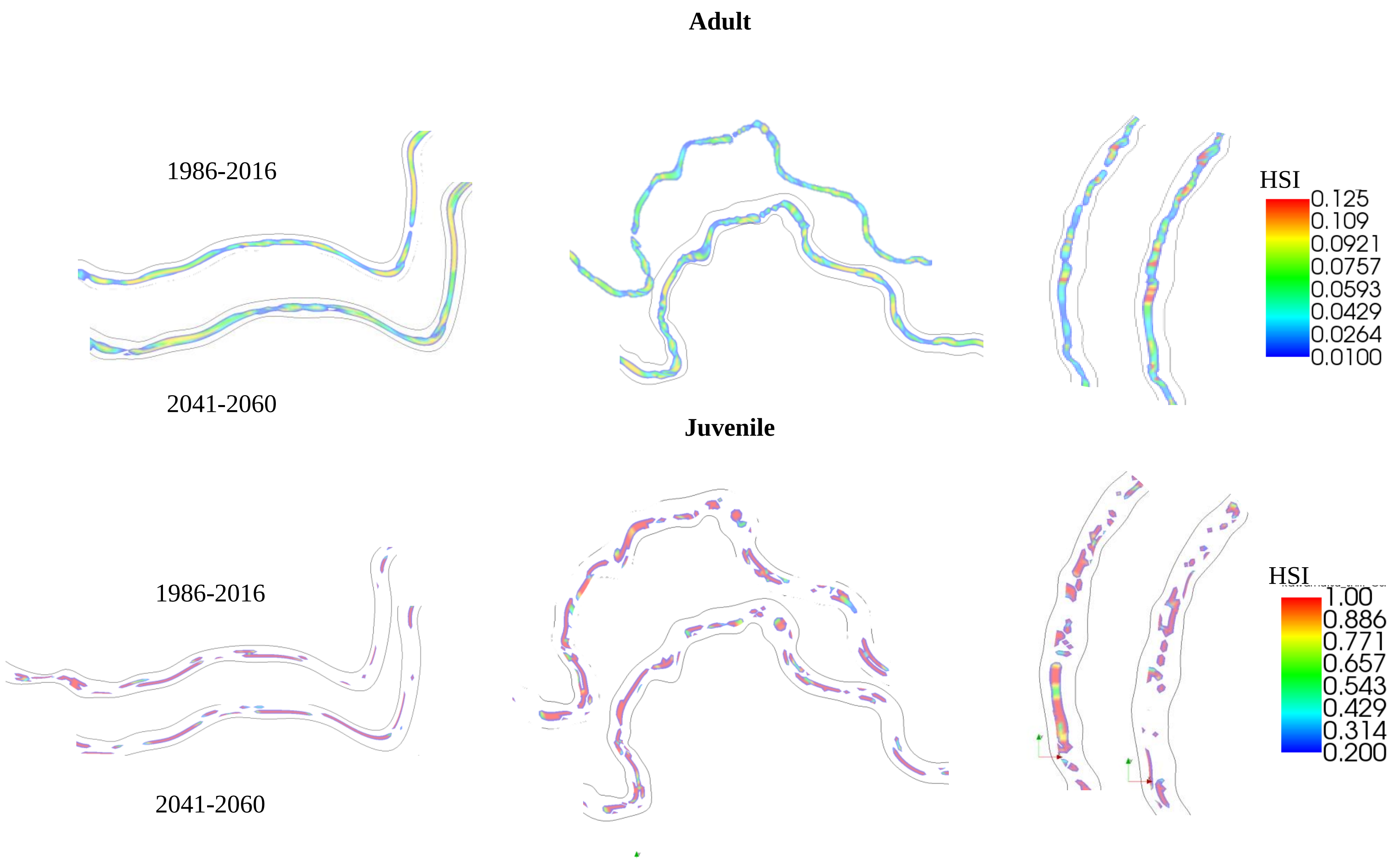
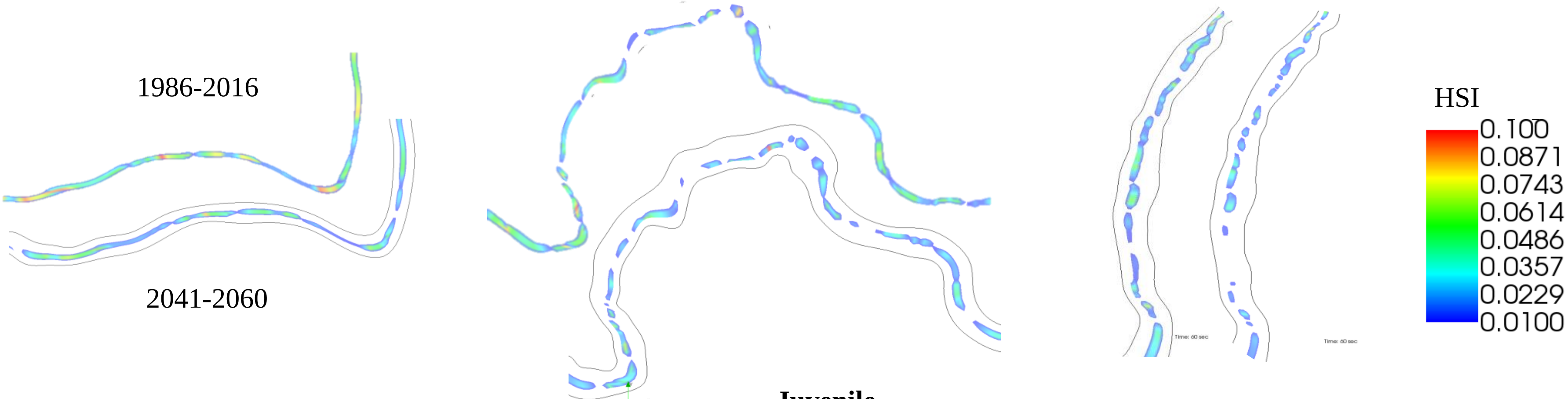


Figure 5-12 HSI for Kawamutsu fish at minimum value of discharge on August

Adult



Juvenile

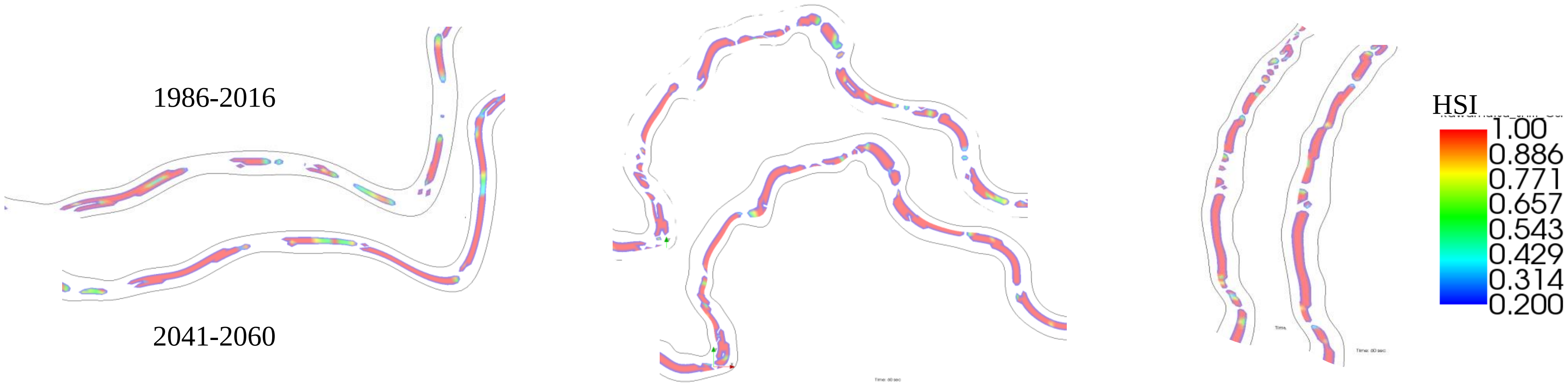
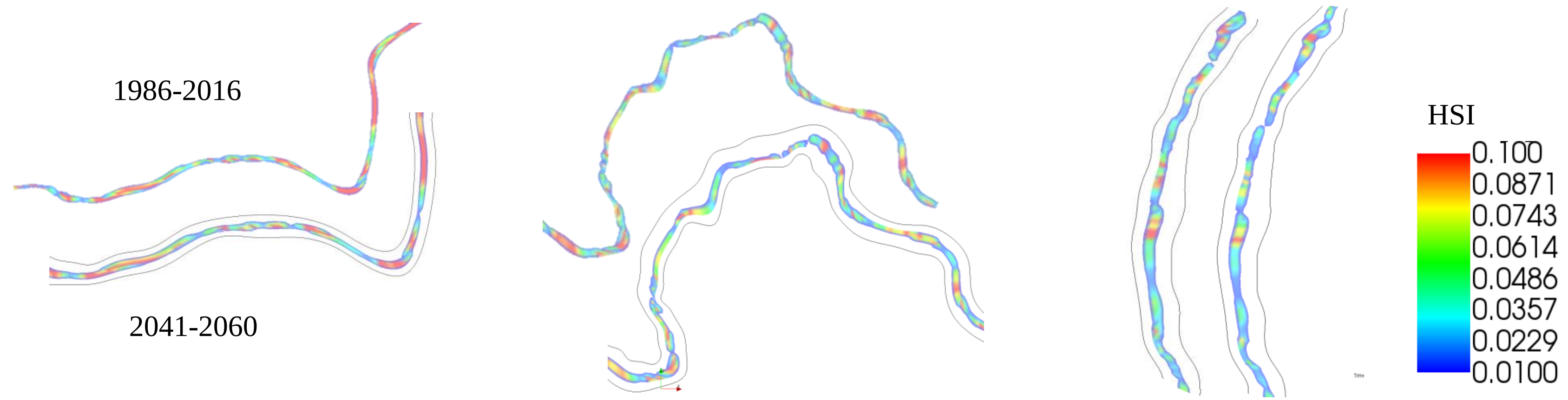


Figure 5-13 HSI for Kawamutsu fish at minimum value of discharge on January

Adult



Juvenile

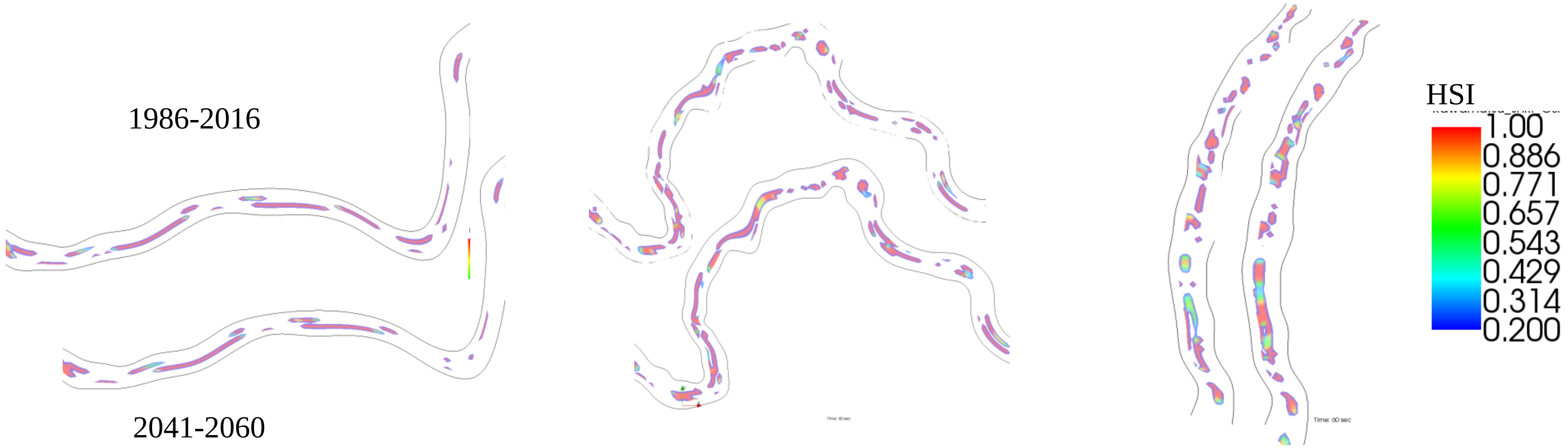
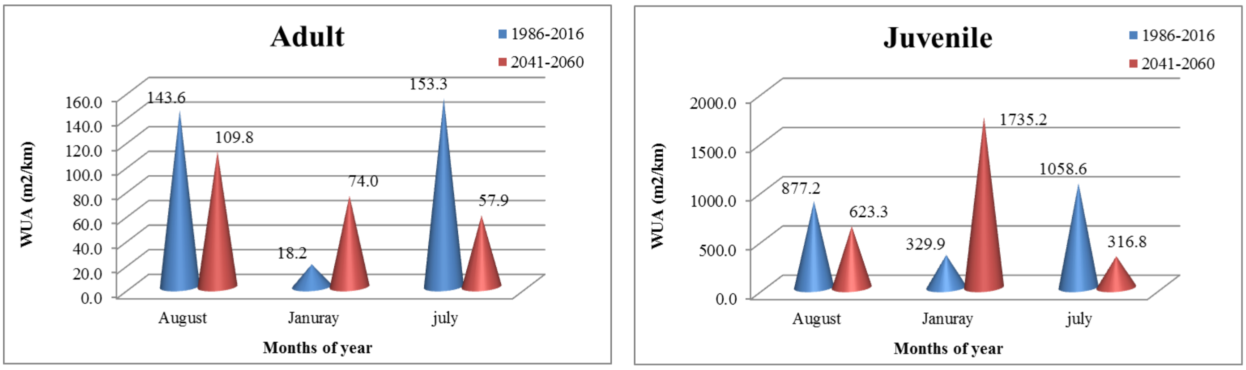
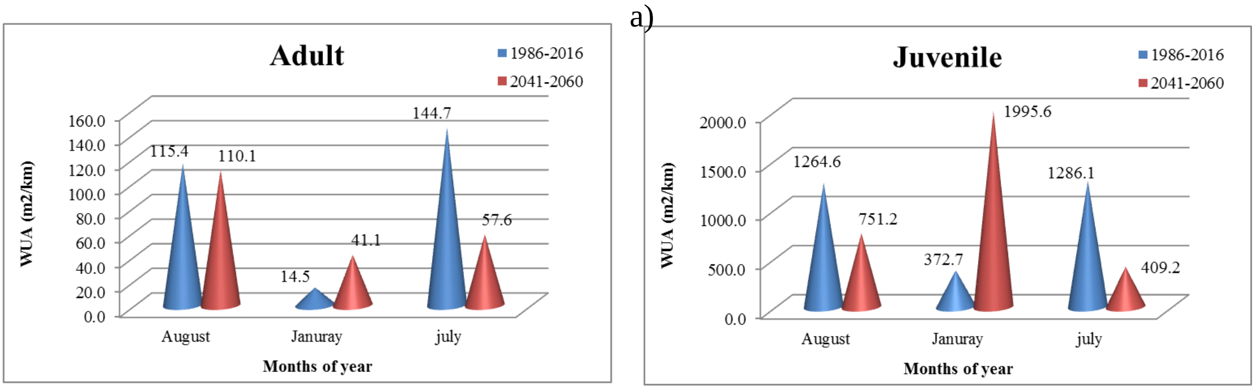


Figure 5-14 HSI for Kawamutsu fish at minimum value of discharge on July

As the result showed, except August in minimum value of discharge, WUA has not notable changes. Then, for the next step water temperature SI for calculating WUA was considered to see to what extend this parameter can affect habitat suitability of target fish. Based on Figure 5-15, reduction of habitat suitability in August and July is visible. The interesting point is that, habitat suitability was predicted to decrease in January in adult stage when only hydraulic parameters were used in WUA calculations, however; by considering water temperature habitat suitability is expected to increase in this month. Moreover, before considering water temperature it was predicted not having sense bale changes in July but there is a notable reduction after considering water temperature in this month.



a)



b)

Figure 5-15 Weighted Usable Arae for Kawamutsu fish in different months with considering water temperature: a) average discharge of the river in the month, b) minimum discharge of the month

Moreover, our research showed that the effects of water temperature is more important than flood. As it is shown in Figure 5-16 WUA is not changing in flood period without considering water temperature for both of target fish, however; it is decreasing when water temperature is evaluated.

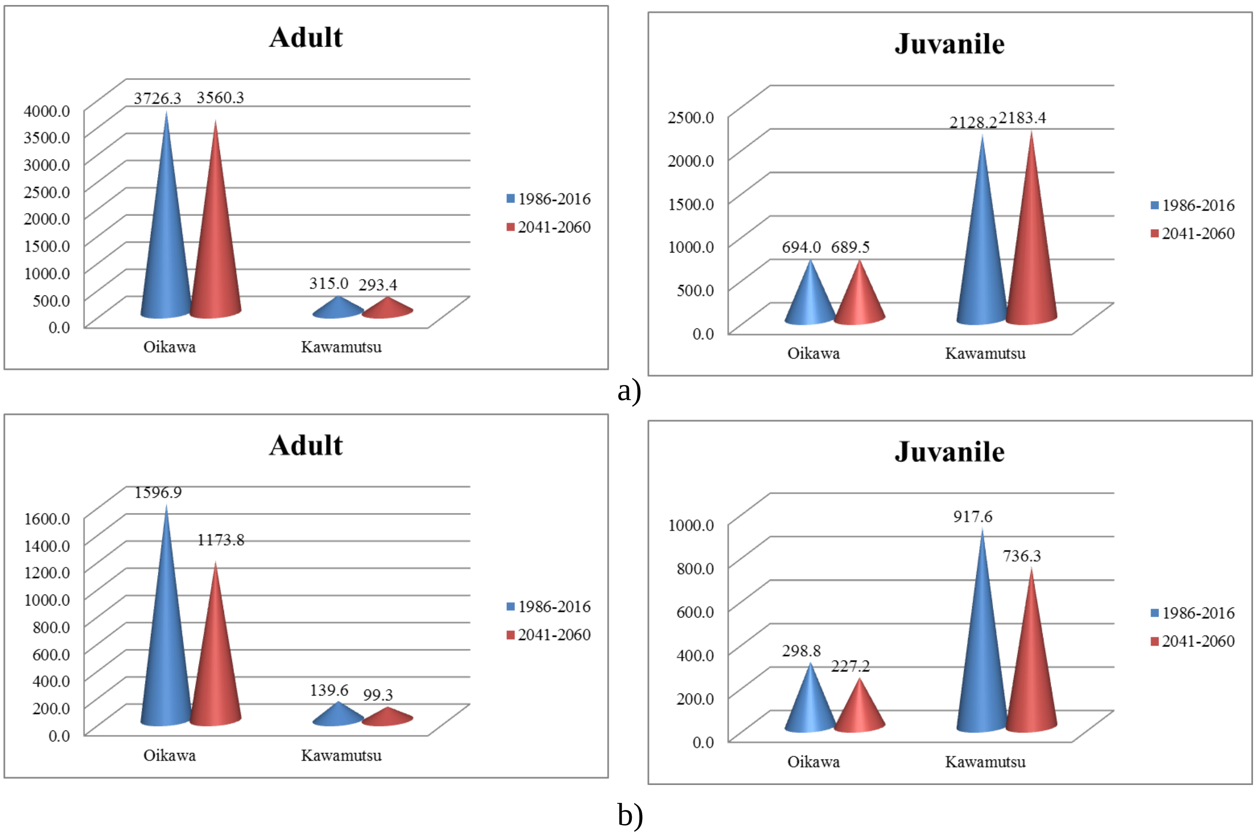


Figure 5-16 Weighted Usable Area for Oikawa and Kawamutsu fish in flood time on August: a) without considering water temperature, b) considering water temperature

5-3. Conclusion

In this chapter, the impact of climate change on habitat suitability was analyzed by using EvaTrip. In this regard, outputs of the SWAT model for MICRO5 (RCP8.5) and HadGEM2-ES (RCP4.5) were used to assess how changes in discharge will affect HSI for Oikawa and Kawamutsu fish by 2060. Moreover, the modified SWAT model water temperature formula made us be able to project water temperature in the future.

Results illustrated that as Oikawa fish prefer low water depth and water velocity, the month of August is not a suitable time for it in both adult and juvenile when the discharge of the river is in its average. However, in the minimum value of river flow WUA in the Kikuchi river for Oikawa is about 4500 (m2/Km) and 800 (m2/km) which is expected to decrease in the future on August, as river discharge will increase even in its minimum value.

At the average value of discharge, it is expected WUA will not change in January and July by 2060. This condition is the same for July at the minimum value of discharge, while; it is expected to decrease in January. This reduction mostly related to the decrease in the area having water. It means that in the future there will be some areas which used to have water but in the future, they do not. So WUA will decrease, although HSI will increase for Oikawa fish.

Based on our result habitat suitability of Kawamutsu fish is not the same for the adult and juvenile stage. It is expected to reduce in January at the average value of discharge in the adult stage, while; it will increase on the Juvenile stage. This is because in the adult stage low water depth and velocity are not the fish preference but it is suitable at the juvenile stage (Figure 5-11). In August, WUA is expected to decrease and in January, HSI will increase at the minimum value of discharge by 2060, respectively. The month of July also does not have a suitable condition for Kawamutsu, except for juveniles at the minimum value of river flow which is supposed to have a slight increase in the future.

On the other hand, water temperature is predicted to increase up to 5 °C, which can be considered as a threat for both target fish especially in July which is spawning time. In other words, *Zacco platypus'* climate zone is 10°C - 22°C (34) and based on our result water temperature is anticipated to increase up to 30°C by 2080. The highest value of the rise in water temperature is happening from November to February which is up to 6°C.

Based on our result:

(1) Changes in hydraulic parameters will not have a notable effect on WUA for Oikawa and Kawamutsu in comparison with the effects of this phenomenon when the water temperature is being considered. It means that WUA is expected to decrease from 4500 (m2/km) to around 4400(m2/km) on August, however; this reduction is from 3000(m2/km) to about 2000 (m2/km) (which is about 1000(m2/km)) when the impact of water temperature affected by climate change was analyzes. This reduction is happening for July as well so that it was expected not having any changes in WUA based on changes in hydraulic parameters while changes in water temperature will decrease WUA up to 60% for both target fish species (Table 5-4 to Table 5-7).

Table 5-4 WUA changes for Oikawa without considering water temperature

	WUA at minimum discharge		**WUA at average discharge**		**Adult**	
	1986-2016	2041-2060	1986-2016	2041-2060	%	
August	4522.1	4466.3	4248.5	4025.0	-1	-5
January	4361.1	4158.8	44262.3	43831.4	-5	-1
July	4553.0	4537.0	3634.6	3813.8	0	5
	WUA at minimum discharge		**WUA at average discharge**		**Juvenile**	
	1986-2016	2041-2060	1986-2016	2041-2060	%	
August	794.1	774.0	720.3	698.7	-3	-3
January	718.1	701.5	7132.0	7159.9	-2	0
July	796.2	796.6	685.5	698.2	0	2

Table 5-5 WUA changes for Oikawa with considering water temperature

	WUA at minimum discharge		**WUA at average discharge**		**Adult**	
	1986-2016	2041-2060	1986-2016	2041-2060	%	
August	2070.4	1495.4	1849.8	1279.9	-28	-31
Januray	441.4	2012.8	445.9	2128.0	78	79
july	2292.2	821.1	1793.1	600.1	-64	-67
	WUA at minimum discharge		**WUA at average discharge**		**Juvenile**	
	1986-2016	2041-2060	1986-2016	2041-2060	%	
August	349.7	238.2	299.3	213.6	-32	-29
Januray	72.9	340.0	71.8	348.1	79	79
july	387.7	126.3	336.9	111.4	-67	-67

Table 5-6 WUA changes for Kawamutsu without considering water temperature

	WUA at minimum discharge		**WUA at average discharge**		**Adult**	
	1986-2016	2041-2060	1986-2016	2041-2060	%	
August	225.2	288.6	309.8	320.0	28	3
January	143.3	85.5	1805.6	1537.3	-40	-15
July	266.3	238.6	305.3	321.8	-10	5
	WUA at minimum discharge		**WUA at average discharge**		**Juvenile**	
	1986-2016	2041-2060	1986-2016	2041-2060	%	
August	3021.9	2413.3	2094.4	2029.5	-20	-3
January	3679.7	4115.7	32804.3	35612.2	12	9
July	2681.9	2918.5	2134.8	2096.0	9	-2

Table 5-7 WUA changes for Kawamutsu with considering water temperature

	WUA at minimum discharge		**WUA at average discharge**		**Adult**	
	1986-2016	2041-2060	1986-2016	2041-2060	%	
August	115.4	110.1	143.6	109.8	-5	-24
January	14.5	41.1	18.2	74.0	65	75
July	144.7	57.6	153.3	57.9	-60	-62
	WUA at minimum discharge		**WUA at average discharge**		**Juvenile**	
	1986-2016	2041-2060	1986-2016	2041-2060	%	
August	1264.6	751.2	877.2	623.3	-41	-29
January	372.7	1995.6	329.9	1735.2	81	81
July	1286.1	409.2	1058.6	316.8	-68	-70

(1) Water temperature increased for all climate change scenarios which is increasing WUA in January up to 80% for both target fish.

(2) Climate change is expected to move the spawning time and reduce the negative impacts on the target fish in January.

Therefore, as iRIC software shows changes in each cell of the river grid it would be great if prediction of the habitat quality and distribution fish species will be done with different ecotypes. Moreover, focusing on the effects of other factors such as water quality or biological factors (including food resources and predators).

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Appendix

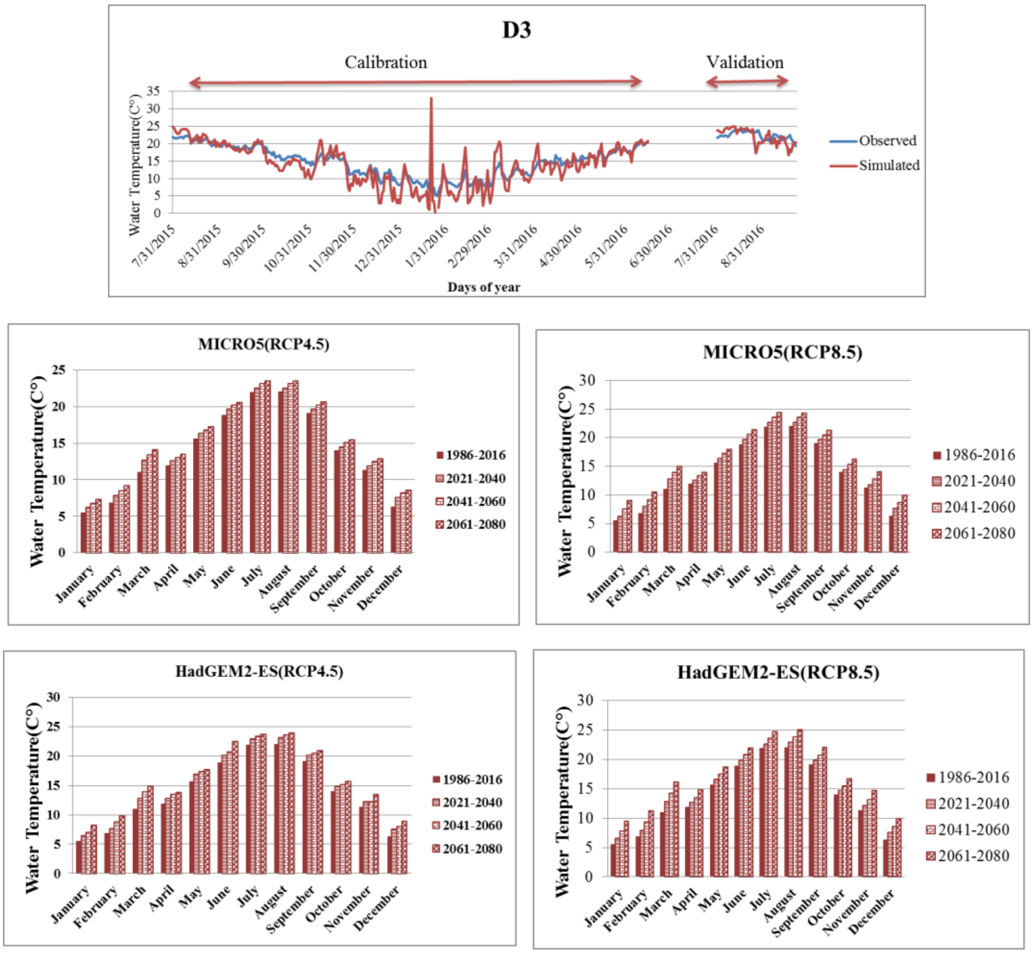

Figure 5-17 Water temperture simulations after calibration and validation for D3 station

Table 5-8 Water temperature changes at D3 station (°C)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
MICRO5(RCP4.5)	2021-2040	1	1	2	1	1	1	1	0	0	0	0	1	1
	2041-2060	1	2	2	1	1	1	1	1	1	1	1	2	1
	2061-2080	2	2	3	2	2	2	2	1	1	1	1	2	2
MICRO5(RCP8.5)	2021-2040	1	1	2	1	1	1	1	1	1	1	0	1	1
	2041-2060	2	2	3	2	2	2	2	1	1	1	1	2	2
	2061-2080	4	4	4	2	2	2	2	2	2	2	3	4	3
HadGEM2-ES(RCP4.5)	2021-2040	1	1	2	1	1	1	1	1	1	1	1	1	1
	2041-2060	1	2	3	1	2	2	1	1	1	1	1	2	2
	2061-2080	3	3	4	2	2	4	2	2	2	2	2	3	2
HadGEM2-ES(RCP8.5)	2021-2040	1	1	2	1	1	1	1	1	1	1	1	1	1
	2041-2060	2	3	3	2	2	2	2	2	2	2	2	2	2
	2061-2080	4	4	5	3	3	3	3	3	3	3	3	4	3

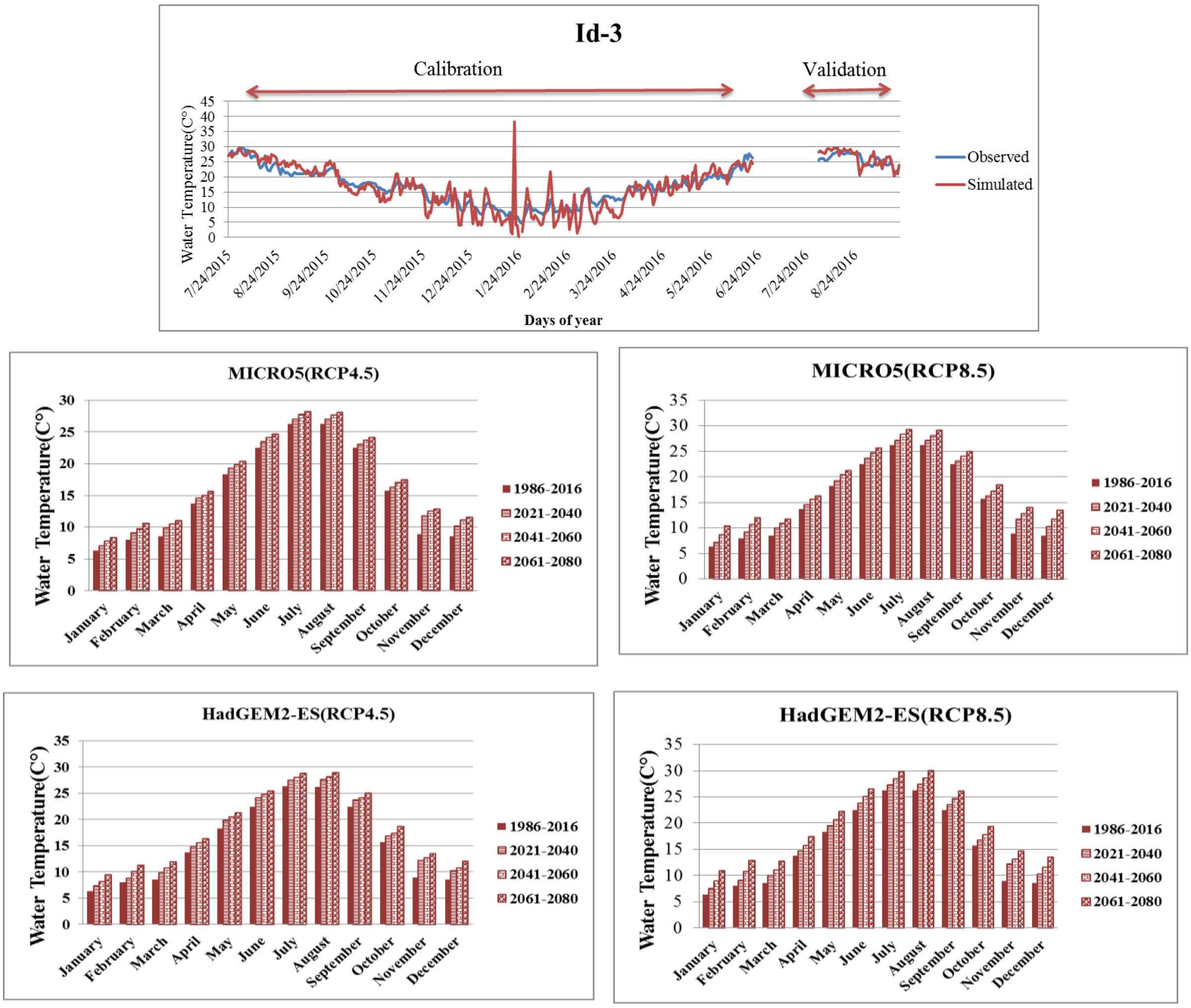

Figure 5-18 Water temperture simulations after calibration and validation for Id-3 station

Table 5-9 Water temperature changes at Id3 station (°C)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
MICRO5(RCP4.5)	**2021-2040**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**1**	**3**	**2**	**1**
	2041-2060	**1**	**2**	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**4**	**2**	**2**
	2061-2080	**2**	**3**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**4**	**3**	**2**
MICRO5(RCP8.5)	**2021-2040**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**3**	**2**	**1**
	2041-2060	**2**	**3**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**4**	**3**	**2**
	2061-2080	**4**	**4**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**5**	**5**	**3**
HadGEM2-ES(RCP4.5)	**2021-2040**	**1**	**1**	**1**	**1**	**2**	**2**	**1**	**1**	**1**	**1**	**3**	**2**	**1**
	2041-2060	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**4**	**2**	**2**
	2061-2080	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**5**	**4**	**3**
HadGEM2-ES(RCP8.5)	**2021-2040**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**3**	**2**	**1**
	2041-2060	**3**	**3**	**3**	**2**	**2**	**3**	**2**	**2**	**2**	**2**	**4**	**3**	**3**
	2061-2080	**5**	**5**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**6**	**5**	**4**

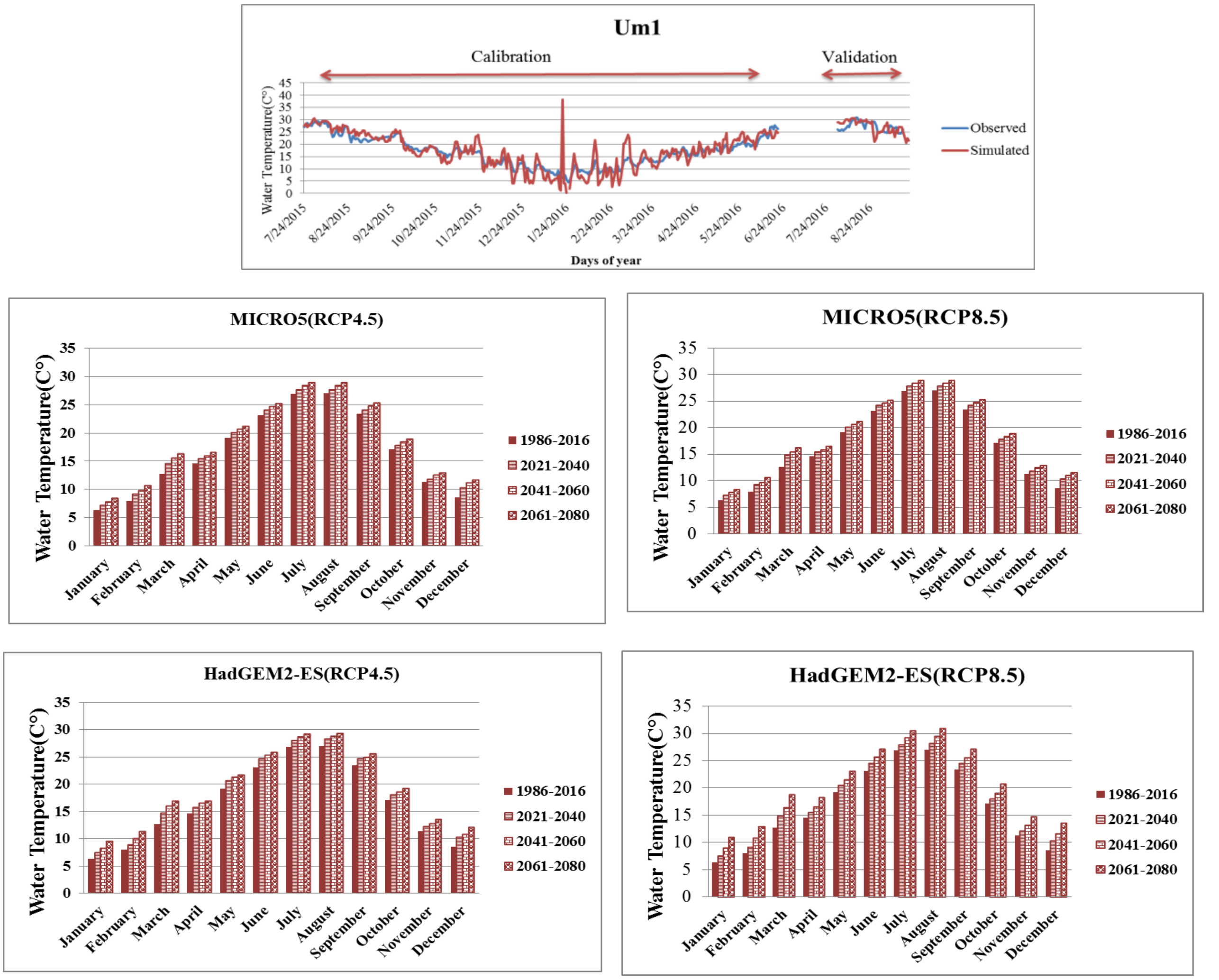

Figure 5-19 Water temperture simulations after calibration and validation for Um1 station

Table 5-10 Water temperature changes at Um1 station (°C)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
MICRO5(RCP4.5)	2021-2040	1	1	2	1	1	1	1	1	1	1	0	2	1
	2041-2060	1	2	3	1	1	2	1	1	1	1	1	2	2
	2061-2080	2	3	4	2	2	2	2	2	2	2	1	3	2
MICRO5(RCP8.5)	2021-2040	1	1	2	1	1	1	1	1	1	1	0	2	1
	2041-2060	2	3	3	2	2	2	2	2	2	2	1	3	2
	2061-2080	4	4	5	3	3	3	3	3	3	3	3	5	3
HadGEM2-ES(RCP4.5)	2021-2040	1	1	2	1	1	1	1	1	1	1	1	2	1
	2041-2060	2	2	3	2	2	2	2	2	1	1	1	2	2
	2061-2080	3	3	4	2	2	3	2	2	2	2	2	3	3
HadGEM2-ES(RCP8.5)	2021-2040	1	1	2	1	1	1	1	1	1	1	1	2	1
	2041-2060	3	3	4	2	2	2	2	2	2	2	2	3	2
	2061-2080	5	5	6	4	4	4	4	4	4	3	3	5	4

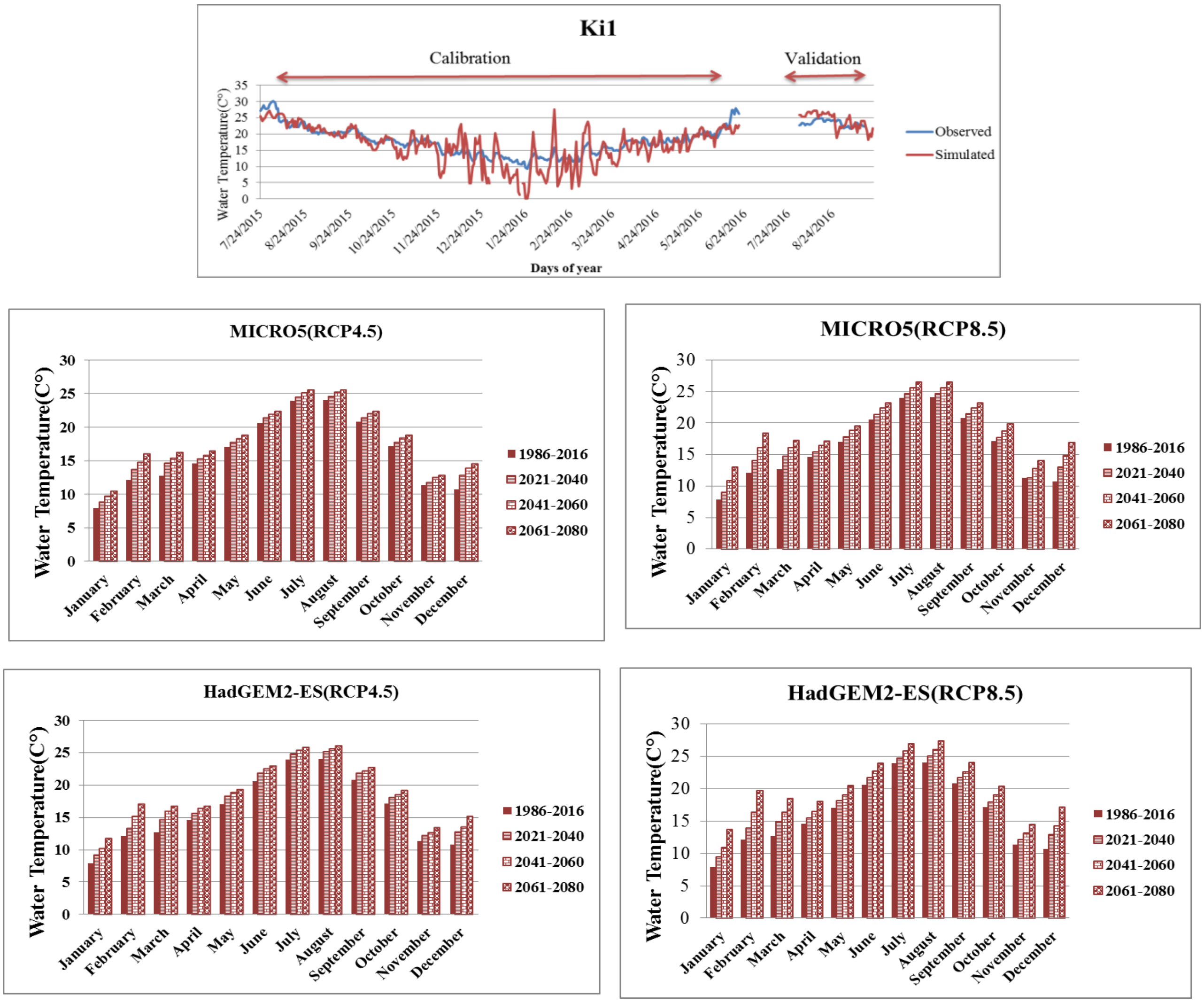

Figure 5-20 Water temperture simulations after calibration and validation for Ki1 station

Table 5-11 Water temperature changes at Ki1 station (°C)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
MICRO5(RCP4.5)	2021-2040	1	2	2	1	1	1	1	1	1	1	0	2	1
	2041-2060	2	3	3	1	1	1	1	1	1	1	1	3	2
	2061-2080	3	4	4	2	2	2	2	2	2	2	1	4	2
MICRO5(RCP8.5)	2021-2040	1	2	2	1	1	1	1	1	1	1	0	2	1
	2041-2060	3	4	3	2	2	2	2	2	2	2	1	4	2
	2061-2080	5	6	5	3	2	3	3	2	2	3	3	6	4
HadGEM2-ES(RCP4.5)	2021-2040	1	1	2	1	1	1	1	1	1	1	1	2	1
	2041-2060	2	3	3	2	2	2	2	2	1	1	1	3	2
	2061-2080	4	5	4	2	2	2	2	2	2	2	2	4	3
HadGEM2-ES(RCP8.5)	2021-2040	2	2	2	1	1	1	1	1	1	1	1	2	1
	2041-2060	3	4	4	2	2	2	2	2	2	2	2	4	3
	2061-2080	6	8	6	3	3	3	3	3	3	3	3	6	4

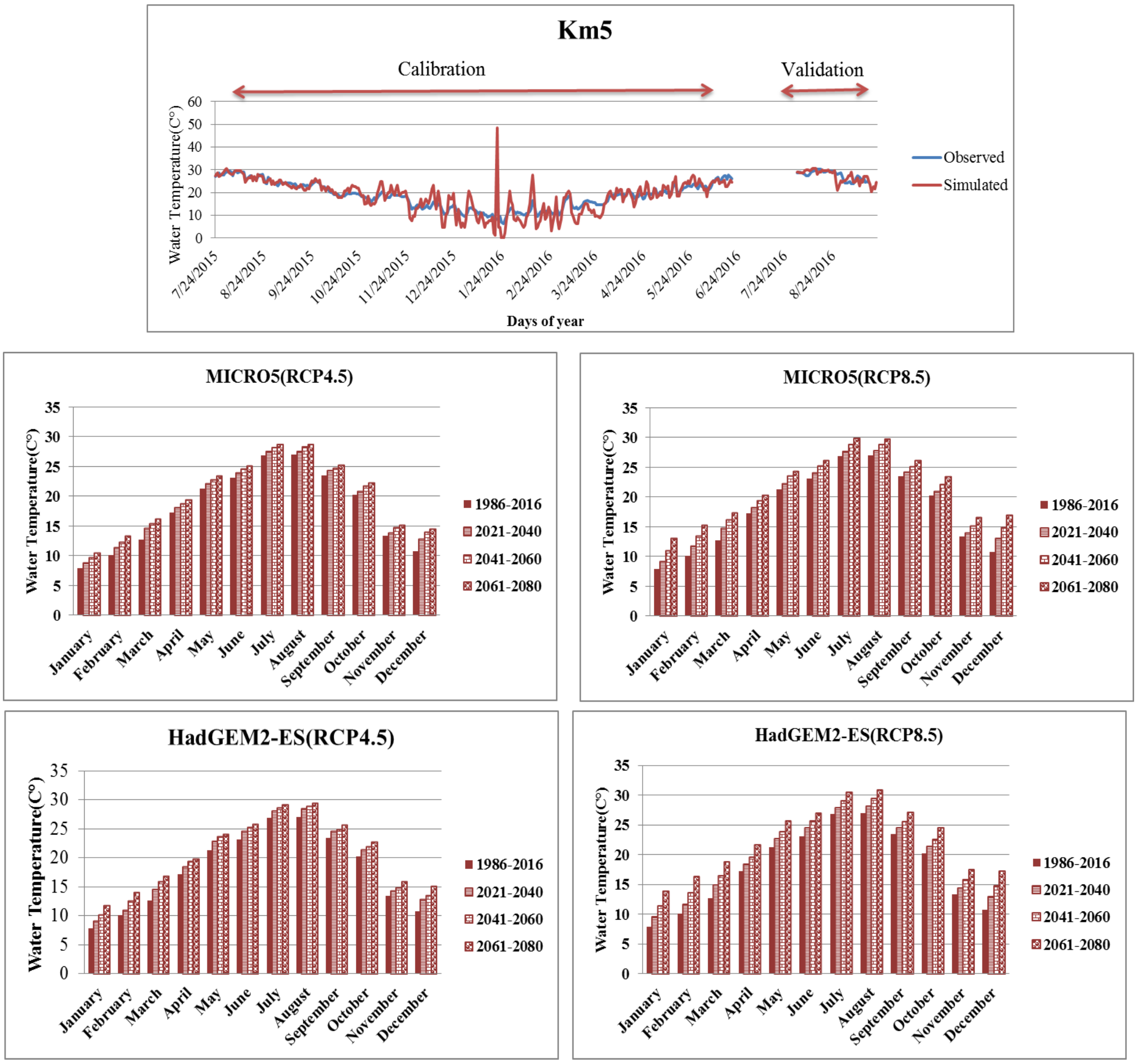

Figure 5-21 Water temperture simulations after calibration and validation for Km5 station

Table 5-12 Water temperature changes at Km5 station (°C)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
MICRO5(RCP4.5)	**2021-2040**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**2**	**1**
	2041-2060	**2**	**2**	**3**	**1**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**3**	**2**
	2061-2080	**3**	**3**	**4**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**4**	**2**
MICRO5(RCP8.5)	**2021-2040**	**1**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**1**
	2041-2060	**3**	**3**	**3**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**4**	**2**
	2061-2080	**5**	**5**	**5**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**6**	**4**
HadGEM2-ES(RCP4.5)	**2021-2040**	**1**	**1**	**2**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**1**
	2041-2060	**2**	**3**	**3**	**2**	**2**	**2**	**2**	**2**	**1**	**2**	**2**	**3**	**2**
	2061-2080	**4**	**4**	**4**	**3**	**3**	**3**	**2**	**2**	**2**	**2**	**3**	**4**	**3**
HadGEM2-ES(RCP8.5)	**2021-2040**	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**1**
	2041-2060	**3**	**4**	**4**	**2**	**3**	**2**	**2**	**2**	**2**	**2**	**2**	**4**	**3**
	2061-2080	**6**	**6**	**6**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**6**	**5**

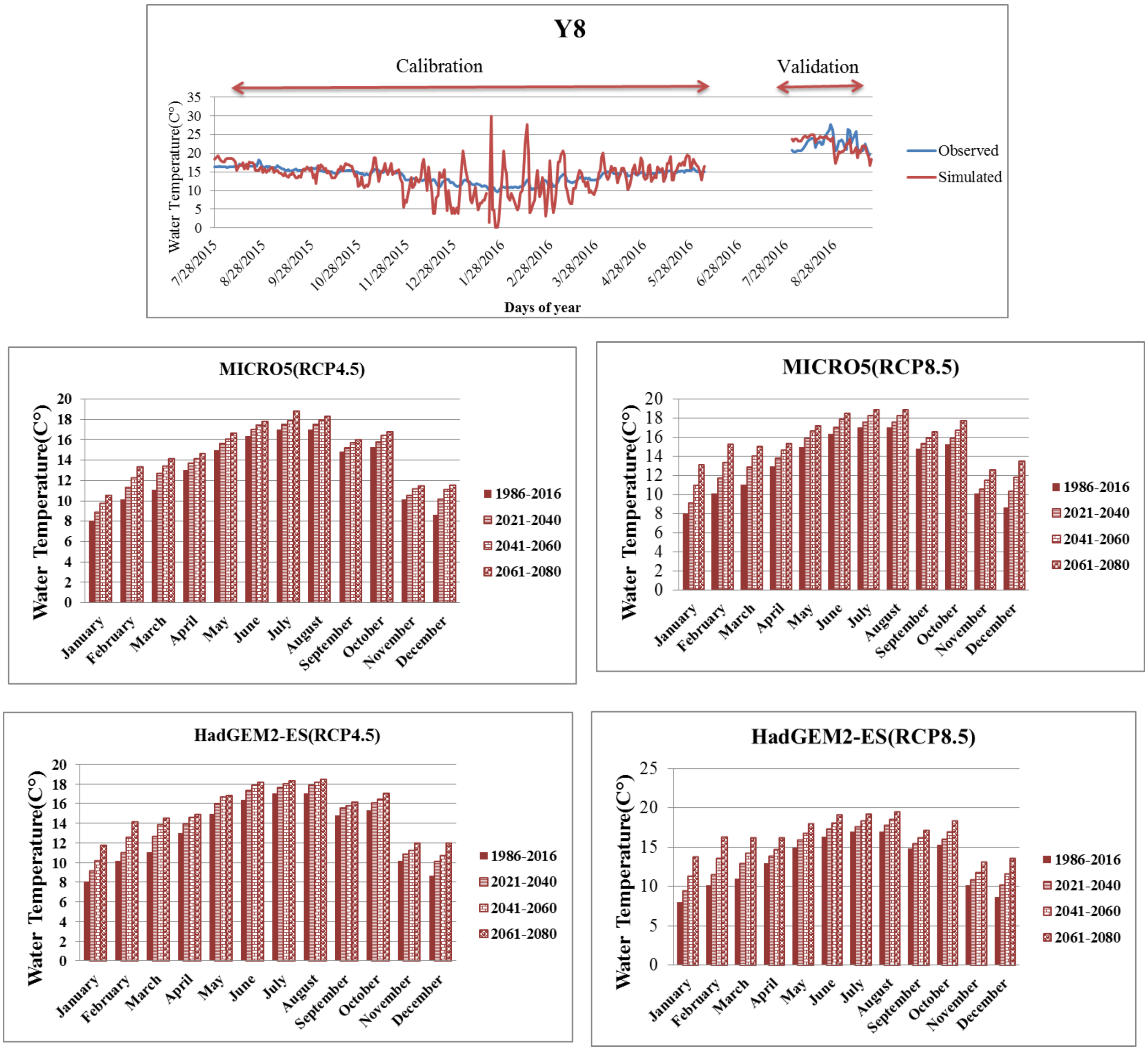

Figure 5-22 Water temperture simulations after calibration and validation for Y8 station

Table 5-13 Water temperature changes at Y8 station (°C)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
MICRO5(RCP4.5)	**2021-2040**	**1**	**1**	**2**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**1**
	2041-2060	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**1**
	2061-2080	**2**	**3**	**3**	**2**	**2**	**1**	**2**	**1**	**1**	**1**	**1**	**3**	**2**
MICRO5(RCP8.5)	**2021-2040**	**1**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**0**	**1**	**0**	**2**	**1**
	2041-2060	**3**	**3**	**3**	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**3**	**2**
	2061-2080	**5**	**5**	**4**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**5**	**3**
HadGEM2-ES(RCP4.5)	**2021-2040**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	2041-2060	**2**	**2**	**3**	**2**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**2**	**2**
	2061-2080	**4**	**4**	**4**	**2**	**2**	**2**	**1**	**2**	**1**	**2**	**2**	**3**	**2**
HadGEM2-ES(RCP8.5)	**2021-2040**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**1**
	2041-2060	**3**	**3**	**3**	**2**	**2**	**2**	**1**	**2**	**1**	**2**	**2**	**3**	**3**
	2061-2080	**6**	**6**	**5**	**3**	**3**	**3**	**2**	**2**	**2**	**3**	**3**	**5**	**6**

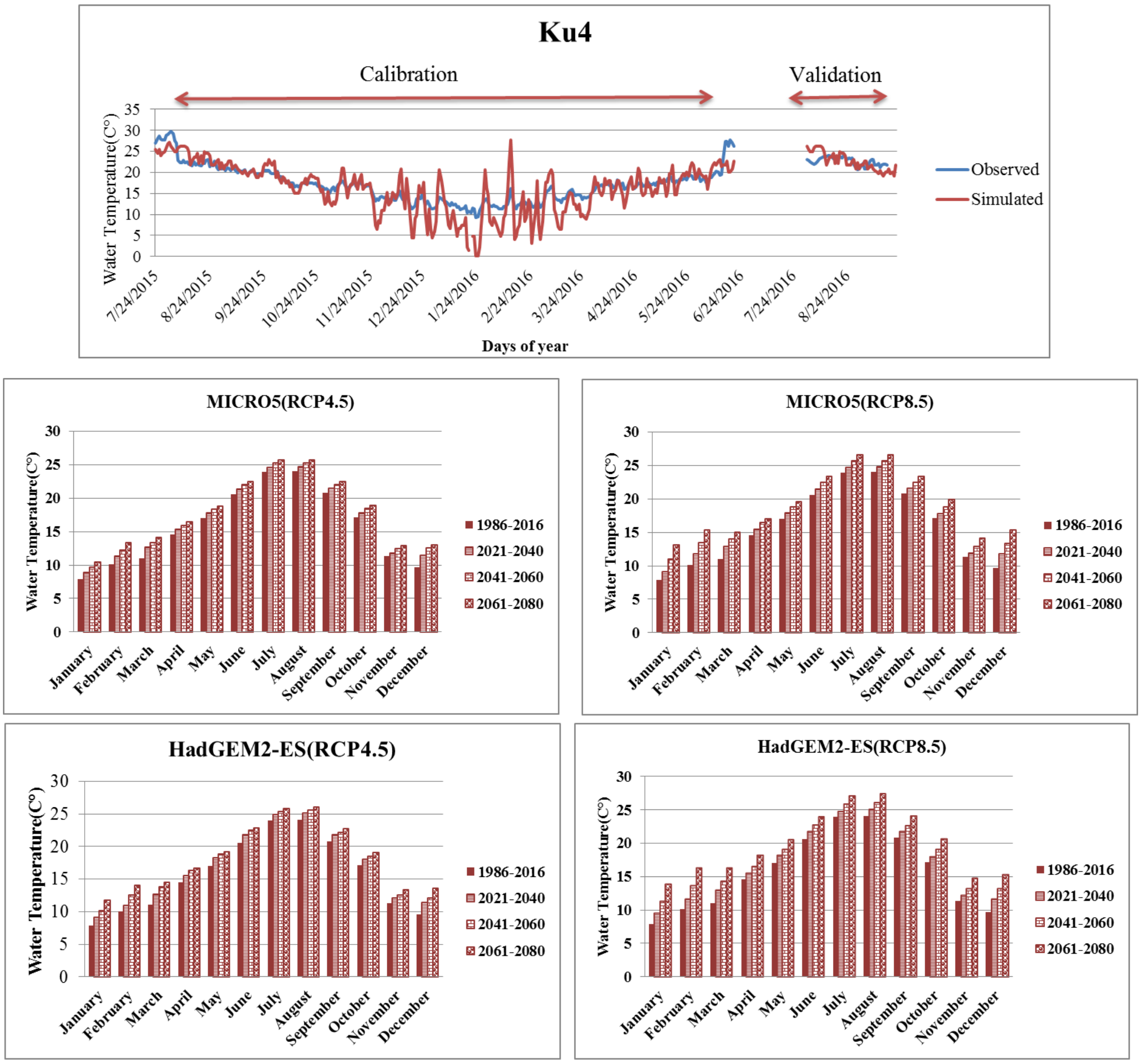

Figure 5-23 Water temperture simulations after calibration and validation for Ku4 station

Table 5-14 Water temperature changes at Ku4 station (°C)

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
MICRO5(RCP4.5)	2021-2040	1	1	2	1	1	1	1	1	1	1	0	2	1
	2041-2060	2	2	2	1	1	1	1	1	1	1	1	3	2
	2061-2080	3	3	3	2	2	2	2	2	2	2	1	3	2
MICRO5(RCP8.5)	2021-2040	1	2	2	1	1	1	1	1	1	1	0	2	1
	2041-2060	3	3	3	2	2	2	2	2	2	2	1	4	2
	2061-2080	5	5	4	2	2	3	3	2	2	3	3	6	3
HadGEM2-ES(RCP4.5)	2021-2040	1	1	2	1	1	1	1	1	1	1	1	2	1
	2041-2060	2	3	3	2	2	2	2	2	1	1	1	2	2
	2061-2080	4	4	4	2	2	2	2	2	2	2	2	4	3
HadGEM2-ES(RCP8.5)	2021-2040	2	2	2	1	1	1	1	1	1	1	1	2	1
	2041-2060	3	4	3	2	2	2	2	2	2	2	2	4	2
	2061-2080	6	6	5	4	3	3	3	3	3	3	3	6	4

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Chapter 6: Conclusion and recommendations

6-1. Conclusion

As it is shown in many studies and IPCC reports climate change effects are known as a threat for future earth which is making scientists working on evaluating and assessing its impacts on earth (1–4). This phenomenon would have different effects on each geographical region so that with rising atmospheric moisture content in a warming climate, dry areas are expected to be drier and wet areas are predicted to be wetter. To predict the future climatic condition, global climate models (GCMs) are being used which are based on the coupled ocean-atmosphere-land system. The Coupled Model Inter-comparison Project Phase 5 (CMIP5) provides historical and future climate datasets including verity models for projecting future climate (5). Downscaled GCMs are widely used in different studies to understand extreme hydrological events caused by climate change.

The main goals of this study were impact assessment of climate change on habitat suitability by 2080. In this regard, projecting future air temperature and precipitation affected by climate change was our first step. So that, climate prediction has been done by using two different GCMs including HadGEM2-ES and MICRO5 under two RCPs (RCP 4.5 and RCP .5) for three 20-years periods (2021-2040, 2041-2060, and 2061-2080). Secondly, the impact of climate change on hydrological and environmental parameters was analyzed by using the SWAT model and IHA. As the third step, changes in hydraulic parameters including water depth and water velocity using Nays2DH in iRIC software were studied. Finally, the impact of climate change on habitat suitability for *Zacco platypus* (Oikawa) and *Zacco temminckii* (Kawamutsu) was assessed by using EvaTrip in iRIC environment. The findings from this study can be concluded as follows:

In chapter 2, assessing the impact of climate change on air temperature in the Kikuchi basin was our main objective. So, data from HadGEM2-ES and MICRO5 models were downscaled by busing LARS-WG software to project how clime change will affect the mentioned meteorological parameter. Because of uncertainties in GCMs especially for Kyushu Island, results showed different projections. In other words, except for the projections for the first future period (2021-2040) in which there is an agreement about decreasing the precipitation under both used GCMs from 250 (mm) to 10 (mm), there are different predictions for the other future periods. It means, under HadGEM2-ES, annual rainfall is expected to increase about 70 (mm) and 50 (mm) in 2041-2060 and 2061-2080, respectively. However, under MICRO5 it is predicted to have a reduction for this meteorological parameter about 200 (mm) and 50 (mm) in 2041-2060 and 2061-2080, respectively. Both models showed average annual air temperature is expected to increase from 15.8 in the baseline period to 18.4 °C (RCP4.5) and 19.7 °C (RCP8.5) based on HadGEM2-ES, as well as; 17.9 °C (RCP4.5) and 19°C (RCP8.5) based on MOICRO5. As these changes will affect the flow regime it was important to work on changes in IHA and EFC to have the best evaluations on river flow in the future.

In chapter 3, the effects of these changes in meteorological parameters on hydrological indicators and environmental components were analyzed. In this regard, the SWAT model was used as a hydrological model to simulate the flow of the Kikuchi River. Then, I analyzed the hydrological and environmental effects of climate change on our case study by using IHA software. Based on MICRO5 prediction under two RCPs, it is expected to have less river flow in the Kikuchi basin up to 6 (m3/s) by 2080. This reduction has been also projected by HadGEM2-ES, except for two future periods including 2041-2060 and 2061-2080 in which streamflow will increase 2 (m3/s) and 1 (m3/s), respectively. This disagreement between these two models is because of having uncertainties in GCMs for Japan. Based on the IHA model output extreme events are expected to increase. For example, the frequency of extreme low flows and the count of high flow pulses are two parameters of EFCs which would be affected more by climate change in comparison with other indicators. For both of these parameters, it is expected to have 60% increase within the next century. These changes will affect the river wide influence on water depth and water velocity. These two parameters have direct impacts on fish habitat suitability so that makes the importance of hydraulic simulations.

In chapter 4, the main purpose was analyzing how climate change is affecting hydraulic parameters in the Kikuchi river, by 2060. The result from chapter 3 showed that the highest and lowest levels of river flow are related to projections from HadGEM2-ES (RCP4.5) and MICRO5 (RCP8.5) in 2041-2060, respectively. By using the output of the SWAT model from these two GCMs, Nays2DH solver in iRIC software was run for three months including August, January, and July. Results showed, despite the water depth and velocity is decreasing in January and July, these hydraulic parameters will increase in August by 2060. It is expected to have more and stronger, floods having various side effects on ecosystem services as well as aquatic habitat suitability.

In chapter 5, the impact of climate change on habitat suitability was analyzed by using EvaTrip solver in iRIC software. In this regard, outputs of the SWAT model for MICRO5 (RCP8.5) and HadGEM2-ES (RCP4.5) were used to assess how changes in discharge will affect HSI for Oikawa and Kawamutsu fish by 2060. I chose the mentioned RCPs of

HadGEM2-ES and MICRO5 as the maximum and minimum changes in the river flow are related to these two, respectively. Moreover, the modified SWAT model water temperature formula made us be able to project water temperature in the future. Results illustrated that as Oikawa fish prefer low water depth and water velocity, the month of August is not a suitable time for it in both adult and juvenile when the discharge of the river is in its average value. However, in the minimum value of river flow WUA in the Kikuchi river for Oikawa is about 4500 (m2/Km) and 800 (m2/km) which is expected to decrease in the future on August, as river discharge will increase even in its minimum value. At the average value of discharge, it is expected WUA will not change in January and July by 2060. This condition is the same for July at the minimum value of discharge, while; it is expected to decrease in January. This reduction mostly related to the decrease in the area having water. It means that in the future there will be some areas which used to have water but in the future, they do not. So WUA will decrease, although HSI will increase for Oikawa fish. Based on our result habitat suitability of Kawamutsu fish is not the same for the adult and juvenile stage. It is expected to reduce in January at the average value of discharge in the adult stage, while; it will increase on the Juvenile stage. This is because of that in adult stage low water depth and velocity are not the fish preference but it is suitable at the juvenile stage. In August, WUA is expected to decrease and in January, HSI will increase at the minimum value of discharge by 2060, respectively. The month of July also does not have a suitable condition for Kawamutsu, except for juveniles at the minimum value of river flow which is supposed to have a slight increase in the future. The important point is that changes in the hydraulic parameter will not have a notable effect on WUA for Oikawa and Kawamutsu in comparison with the effects of this phenomenon when the water temperature is being considered. It means that WUA is expected to decrease from 4500 (m2/km) to around 4400(m2/km) on August, however; this reduction is from 3000(m2/km) to about 2000 (m2/km) (which is about 1000 (m2/km)) when the impact of water temperature affected by climate change was analyzes. This reducing is happening for July as well so that it was expected not having any changes in WUA based on changes in hydraulic parameters while changes in water temperature will decrease WUA up to 60% for both target fish species

6-2. Recommendations

The better understanding of the impacts of climate change on habitat suitability is a real challenge among hydrologists and ecologists so that lots of different methods and models have been developed to reach this goal. Still, there can be more pathways and strategies to improve our vision about the future and impacts of climate change. Therefore, the following recommendations are suggested for the development of future studies:

I. The more variety of GCMs is used, the better the assessment of uncertainties would be achievable.

II. iRIC model has limitations for calculating HSIs. It means, when it is needed to introduced SIs, there are only three options including Sl for water depth, SI for Water velocity and SI for a river bed cover. So, it is not possible to add SI for water temperature. Therefore, it would be great to develop this helpful software for having more space for introducing more SIs.

III. Analyzing changes in water quality such as BOD, COD, and NH4 in the river would be great to have a better vision on habitat suitability as well as ecosystem service capacity.

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