Impacts of Climate Change on Water Resources (A Case Study of Matapedia River, Quebec, Canada)

دراسة تأثير التغيرات المناخية على الموارد المائية (حوض نهر ميتابيدا في مقاطعة كيبك - كندا كحالة دراسية)

Oday Tamween Al-Heetimi (M.Sc) [1] , Dr.Isam Issa Omran (PhD) [2]
oday.alheetimi@gmail.com alomranisam@yahoo.com
Wisam Abidalabbas Abidalla (M.Sc) [3] , Ali Tamween Ajeel [4]
ahmedalisahra@gmail.com ali alheetimi@yahoo.com
[1] State Commission for Dams , Iraq [2,3] Al-Mussaib Technical Institute , Al-Furat Al-Awsat Technical University , 51009 Babylon , Iraq
[4] Ministry of Agriculture Baghdad ,Iraq

Abstract

Changing in universal climate will cause a major effect on hydrological systems which will has a direct impact on ecological, economic and social systems. Climate change will be varied from location to another in the globe, therefore a specific site models are important to determine the impact on the aimed region. In this study the impacts of climate change been analyzed on the Matapedia River watershed located in Quebec, Canada; by developing a hydrological process based model to simulate the current and future river flows and the region precipitation. Matapedia hydrological model used Canadian Regional Circulation Model (CRCM) climate data to simulate future scenario of the watershed. Delta method been used for downscaling and Quantile-Quantile method used to correct the model results distributions. Then used corrected data for the hydrological model for the stream flow records between (1982-2001) to forecast stream flow, precipitations and other climate parameters such as temperature (max, min), wind and humidity. Results shows flow increased in future flow simulation even though extreme flood discharges by some means decreased in study area during winter and spring months due to an increased in maximum and minimum temperature about (2.65°C to 3.02°C) respectively during (2011-2100) period. Also an increase in precipitation in the future about (1.038) in study area headed to make the flood event of 100 and 1000 year return period more extreme.
Key words : Climate Change, Hydrological Model, Delta, Quantile - Quantile, Quebec.

الخلاصة

اتجه البحث نحو دراسة التغيرات المناخية على نطاق الكرة الأرضية وأثرها المباشر على النظام الهيدرولوجي والذي بدوره سيؤثر على الأنظمة البيئية والاقتصادية والاجتماعية . إن التغيرات المناخية تختلف من موقع إلى آخر على سطح الأرض ، تأتي أهمية تبني موديل خاص بموقع معين على سطح الأرض لمعرفة تأثير التغيرات على الموقع موضوع الدراسة . تم تحليل التغيرات المناخية على حوض نهر ميتابيدا الواقع في كيبك الكندية من خلال تطوير نموذج هيدرولوجي يعمل على محاكاة كميات الجريان الحالية والمستقبلية إضافة إلى كميات السقيط بالمنطقة . استخدم النموذج الكندي للتغير المناخي لغرض التنبؤ بالمناخ ومحاكاة التغيرات التي ستطرأ على حوض التغذية . استخدمت طريقة دلتا لغرض تقليص نطاق الأبعاد وطريقة كونتايل - كونتايل لغرض تصحيح نتائج توزيع النموذج . النتائج المصححة استخدمت بالنموذج الهيدرولوجي مع بيانات الجريان الهيدرولوجي للفترة من 1982 - 2001 لغرض التنبؤ بكميات الجريان والسقيط وباقي العوامل المناخية الأخرى كدرجة الحرارة العظمى والصغرى والرياح والرطوبة . أظهرت النتائج زيادة بمعدلات الجريان المستقبلية بالرغم من تناقص قيم الفيضانات القصوى لمنطقة الدراسة خلال فصلي الشتاء والربيع ناتجة عن ازدياد درجات الحرارة العظمى بمقدار 2.65 والصغرى بمقدار 3.02 للفترة من 2011 - 2100 . كما أشارت إلى ازدياد كميات الأحداث الفيضانية بفترات عودة 100 ، 1000 سنة ذات شدة عالية .
الكلمات الدالة : التغير المناخي ، نموذج هيدرولوجي ، طريقة دلتا ، طريقة كونتايل - كونتايل ، مقاطعة كيبك

Introduction

Earth orbit climate has been changed constantly over it is age. In the past the earthly changes were mostly under the influence of small variations in Earth's orbit which induced a change in the amount of solar energy received by the plant. While; current changes in warmer climate are naturally occurring greatly by human activities which include mostly the burning of fossil fuels and land use changes so; these are currently believed the reason of growing the atmospheric concentration of greenhouse gases .This will in turn to increase temperature of the atmosphere which leads to changing in climate. In result will induce indirect effects in the regional and local hydrological regimes. There are many climate-change impact researches on future hydrological regimes have been done in last decade for examine, gave explanation and quantify the influence of climate changes on hydrological regime in specific regions through analyzing climate variables such as temperature and precipitation. Climate variables are usually analysis by applying either statistical downscaling or dynamical downscaling to convert Global Climate Models (GCM) output results into meteorological variables associated with the selected watershed that can be applying it to a local hydrological model. To simulate the current climate and derived scenarios for future climate GCMs have been used. Due to the large scale of (GCM) which is between 250 to 600 km latitude and longitude and complexity of climate system resulted un ability to represent local sub-grid scale climate variables and dynamics of the climate system. Moreover GCMs are not designed to evaluate hydrological reactions to climate change on specific region. Consequently; regional climate models (RCMs) are applied to examine the impact of climate change on the local or site specific watersheds, thus a hydrological model that simulates sub-grid scale to perform the analysis of hydrological response to climate change for the same area. Those models need input data precipitation and temperature at similar sub grid scale which are usually obtained by adapting the GCM or RCM outputs into trustworthy daily rainfall series at the particular watershed [1]. There are two type of downscaling methods are used which is include dynamic and statistical methods to adjust GCM and RCM data for local hydrological climate models. [2] explained that GCMs are a powerful tool for quantitative analysis of climate change. Though these predictions are fairly accurate on a global or large regional level, the coarse grid of GCMs does not provide an accurate prediction of future conditions in small watersheds or specific sites. The hydrological models are associated to small scale processes and require local climate data as an input, associated to a sub-grid scale. Therefore, there should be a mean to solve such issue by using a downscaling technique. In order to estimate the future climate variables in the watershed, the output from the GCMs must be corrected and adapted to the local area; given raise to regional climate models (RCMs). This correction must be able to incorporate and consider the future environmental conditions. Several downscaling techniques are available in the literature, which are mainly grouped into dynamical and statistical downscaling. The Canadian RCM (CRCM) have been used in this work which was developed through cooperation between the Canadian Regional Climate Modeling and Diagnostics Network funded by Canadian Foundation for Climate and Atmospheric Sciences, Centre for the Study and the Climate Simulation at the Regional Scale of University of Quebec in Montreal, Canadian Centre for Climate Modelling and Analysis and the Ouranos Consortium. [3] investigated impacts the climate change on the hydrology in four semi-urban watersheds in southern Ontario.Three hydrologic models are used and coupled with the bias corrected RCMs data to simulate current and future flow. Flow simulation results show a good agreement with the observed flow for future period (2050s) , also; shows a significant increases in peak and low flow magnitude are predicted for higher return periods 20-100 years. Future climate scenario simulation results shows increases in annual precipitation between 5-8% , also; increases in mean annual daily mean temperature about 2.6-3.2 ^{o}C. [4] investigated the uncertainties related to downscaling techniques using CRCM for a local watershed in Quebec, Canada. Results shows downscaling methods suggest increases in temperature over the basin for the 2085 horizon, where largest increase was predicted for the autumn and winter period by regression based statistical method. Predicted changes for precipitation were not as unequivocal as those for temperature and the analysis showed prediction of future precipitation is greatly influenced by selection of downscaling method and seasons. Trending the six methods showed a general increase in discharge was reported for winter period while decreases in summer. Further trend analysis of the six downscaling techniques indicated that results in the precipitation are highly dependable on the applied downscaling methodology. [5] examined the hydrological regimes of the St. Lawrence tributaries (Quebec, Canada) in case of future changes under the influence of climatic and hydrological data from 1932 to 2005 and future flows and precipitation in the 2020s, 2050s and 2080 by using the delta method as a downscaling approach. Results indicated that the increase in air temperature during the winter/spring period (February to April) will cause a significant decrease in the proportion of precipitation falling as snow, which will cause a reduction in the volume of water stored into snow pack and lead to increases in winter runoff of hydrological regime for Lawrence St. watershed. Aim of this work is to validate a created process based hydrological model and address the impact of climate change on climate variables such as precipitation and temperature. Future flows through the Matapedia river watershed located in Quebec, Canada will be predictedand compared with local hydrological models. In addition assessments on the impact of climate change on the nearby regions environment, social and economic are discussed.

2. Methodology

2.1 Study Area

This research is carried out on the Matapedia river watershed which is located in south- central of Quebec (Canada) as shown in **Figure 1**. The flow station 01BD008 located near Amqui in Quebec, Canada with latitude 48°29'30.0¨ N and longitude 67°26'60.0¨ W .

2.2 Data Presentation

The flow station 01BD008 data were obtained from Environment Canada’s national water data. This data used for developing the climate change model with Daily historical records between (1982-2001) and total drainage area 558 km^2 for the Matapedia river watershed . Due to long time series to present here in this research; although the daily data will be used in hydrological model, nevertheless mean monthly records will be presented in **Table 1.** Climate station (Lac humqui) been used for validation which is located neighbor to the watershed with records between (1972 – 2006). The climate station data been acquired from the Canadian Daily Climate Data (CDCD) database, so climate data extracted by using Green Kenue software. Green Kenue is an advanced data preparation, analysis, and visualization tool for hydrologic modelers, which provides an interface to Environment Canada's hydrometric station database (HYDAT) as well as the Canadian Daily Climate Database (CDCD). Stations are queried interactively and available time series data can be extracted, re-sampled, analyzed, and processed with various editors and calculators. Lac humqui station chooses due to it meets the necessary criteria which has a distance less than 50 km , has a natural regulation with a drainage area less than 1000 km^2, an active station and has continuous flow and level measurements. In addition the Canadian Regional Circulation Model (CRCM) output was uploaded and used to extract future time series of the CRCM data at the chosen climate station.

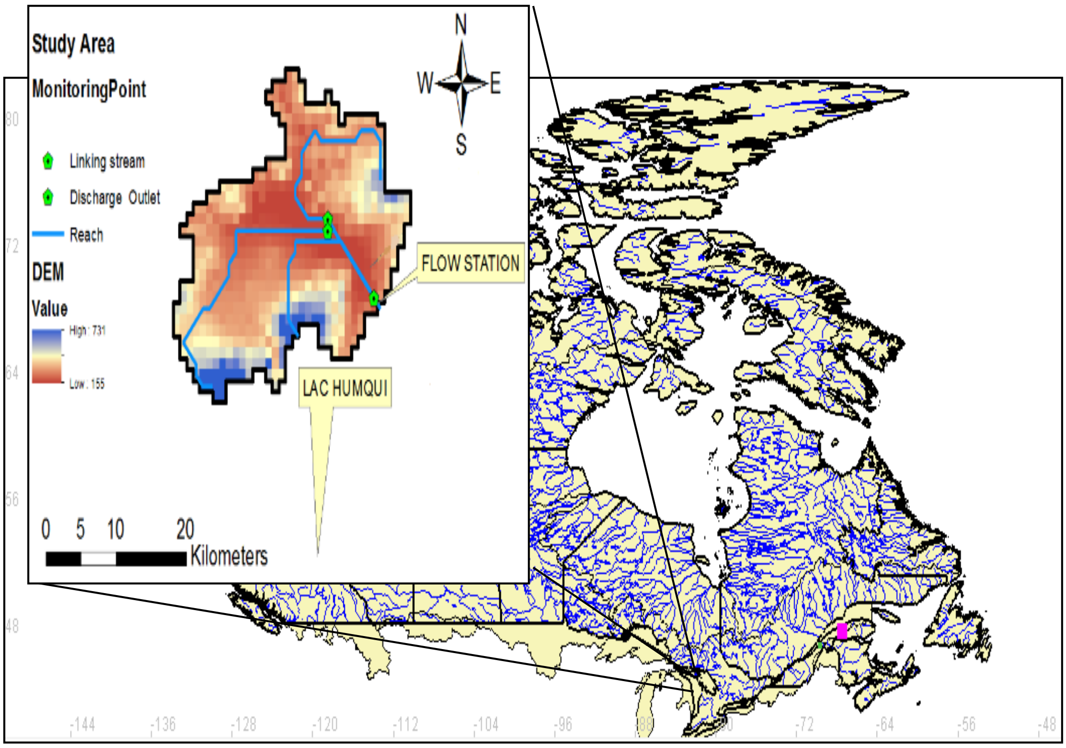


Figure 1. Illustrate The Matapedia River Watershed, Quebec, Canada.

2.3 Hydrological Model Development

Hydrological models are a way that can enable transforming observed precipitations into stream flow at given point for given climatic condition and simulate stream flow by performing an analysis on the climate over a given watershed. Since stream flow is not directly related to precipitation the recreation of the hydrological cycle is complex and thus the simulation of stream flow is not without its challenges. A common hydrological model is process based model. To create a good process based hydrologic model requires improve of many fundamental challenges.(i) to simulate the energy ,momentum and water flux for different subsystem within the domain of the model needs definition of appropriate equations; (ii) the hydrological variability with the processes biophysical of across a hierarchy of scales must be representing ; (iii) the equations of model must be solve; (iv) the model parameters and input data should be estimating; and (v) uncertainty characterizing model. Numerous of these challenges were expressed by [6] and have taken the hydrological research attention over community the last decades [7][8][9][10][11]. Such a model is used to describes the movement of water above and under the soil surface.

Table 1. Mean Monthly Records for Flow Station **01BD008 in** Matapedia River Watershed (m^3/sec)

ID	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
01BD008	1982										1.1	2.57	4.89
01BD008	1983	5.02	3.82	4.11	26.4	60.6	20.5	5.23	2.3	1.97	1.95	4.75	9.62
01BD008	1984	5.18	3.54	3.67	14.6	63.8	28.6	8.42	5.9	3.71	2.44	5.81	9
01BD008	1985	5.04	2.91	2.68	5.08	34.6	16.6	9.55	5.05	3.08	4.64	4.09	3.86
01BD008	1986	3.39	5.13	3.32	24.3	38	16	9.52	7.46	10	8.37	8.4	5.11
01BD008	1987	3.09	1.91	1.53	27.2	13.2	5	5.9	3.12	1.66	1.81	2.49	7.39
01BD008	1988	3.93	2.9	2.66	19.4	38.5	14.1	10.8	4.09	4.18	6.15	11.2	6.49
01BD008	1989	3.9	2.4	2.94	16.2	41.4	19.4	5.68	4.01	2.42	1.43	3.36	3.47
01BD008	1990	2.87	2.65	2.35	10.6	39.6	14	4.17	2.3	0.935	7.99	13.9	11
01BD008	1991	6.33	3.93	4.25	22.4	71.9	22.1	7.04	4.24	2.67	7.27	7.91	7.6
01BD008	1992	7.91	4.83	3.5	15.2	46.4	16	13.6	15.3	4.9	3.53	7.15	4.81
01BD008	1993	3.33	2.65	2.61	23.7	43.2	19.7	5.89	4.8	5.31	10.5	14.1	13
01BD008	1994	6.36	3.68	3.82	14.9	52.6	29.4	13.8	4.66	2.01	1.21	11.2	7.37
01BD008	1995	4.43	4.15	3.45	11.2	60.1	23.4	5.28	2.38	0.684	1.07		
01BD008	1996										1.07	4.01	9.96
01BD008	1997	6.22	3.08	2.25	5.84	49.2	27.6	10.5	3.13				1.82
01BD008	1998	1.73	1.51	4.49	23.6	26.4	8.5	4.6	2.51	3.24	9.03	8.55	8.05
01BD008	1999	5.74	4.73	4.92	20.3	50.8	16.2	4.62	1.7	1.9	3.72	8.15	14.8
01BD008	2000	6.06	3.48	6.53	32.5	41.4	16.8	8.42	4.35	1.52	0.883	4.71	6.65
01BD008	2001	5.1	3.31	2.39	7.38	38.5	15.5	9.29	3.91	2.16			

Hydrological simulations were performed with the process based model. This model tries to represent the physical process of hydrological cycle over catchment area, hence the processes and the equations governing the model depends of the model inputs and climate variation. This model focuses on convince hydrological processes and linked them with runoff model based to simulate flow on the aimed watershed. Thus, for the current study the Seidou model was chosen due to the fact that it was created for a watershed within close proximity of the Matapedia river watershed. The Seidou model focuses on certain hydrological processes and combines them with a runoff model based on the unit hydrograph to simulate stream flow for a given watershed **Figure 2** shows the flow chart that illustrated the relations in the hydrological model components.

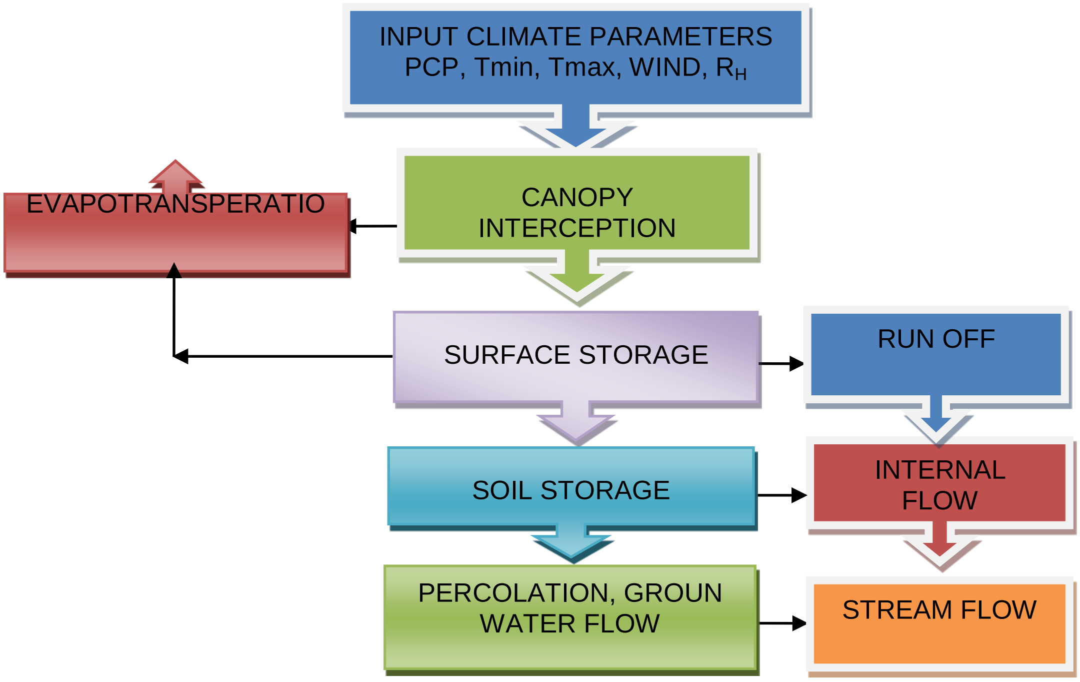


Figure 2. Process Based Model Components Flow chart.

The generated process based model contains three main storage units which is canopy storage, surface storage and soil storage. Flows of precipitation, groundwater flow and runoff then either provide for these storage units or are created when there is an excess of water or a specific condition is met. The inputs for this model are daily averages of precipitation, minimum temperature, and maximum temperature, wind and relative humidity. These daily time series should be taken from meteorological stations that are within 50 km of the studied watershed and contain sufficient overlapping climate data. In addition reference evapotranspiration (ET_o) should be calculated that can be used in the process based model which is compute by using the following equation:

$$ET_o = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T+273} U2(es - ea)}{\Delta + \gamma(1 + 0.34U2)} \qquad (1)$$

Where :

ET_o = Evapotranspiration . [mm day^{-1}] , Rn = Crop surface net radiation [MJ m^{-2} day^{-1}] G = soil density heat flux [MJ m^{-2} day^{-1}] , T = Temperature of air at height of 2 m [°C], U2 = Velocity of wind at 2 m height [m s^{-1}] , es = Vapour pressure saturated [kPa], ea = Vapour pressure actual [kPa] , es - ea = Deficit of vapour pressure saturation

Δ = Slope curve for vapour pressure [kPa °C^{-1}] .

Parameters such as storage volumes, infiltration and percolation, as well as snowmelt and base flow coefficients can be modified by the user in order to attain an optimum simulation. For study area which is the Matapedia river watershed the climate data was taken from a single climate station closest to the stream flow gauging station. Observed discharge was taken from the Environment Canada's hydrometric station database (HYDAT) and is compared to the discharge simulated by the model.

2.4 Downscaling methods

Downscaling is a way to obtain higher spatial resolution output based on GCMs. It is used due to GCM consider the precipitation and temperatures over a 300 km by 300 km and several watersheds are much smaller and spatial variability is important for simulation of hydrological variables. There are two downscaling methods are commonly used. The first type of technique is dynamic downscaling, which corrects the GCM's coarse grid (300 km) to a finer grid (10-50 km) by solving the process based physical dynamics associate to a regional climate system. The second downscaling technique considers statistical relationships between the local variables and the Global or Regional output. It is establish quantitative relationship between model predictors and local variables using historical observed and model predicted data in order to adjust the future prediction in the zone to the local watershed. Statistical downscaling is preferable over dynamical downscaling as it is easy to apply and does not require much computational power. For the purposes of this project, we chose to use statistical downscaling based on the transfer function method. Since the Canadian regional climate model (CRCM) simulation is available for the area of interest and time span selected for the study, we chose to use this data for our simulations. Two statistical downscaling methods are used: the delta method and the Quantile-Quantile (QQ) method.

2.4.1 Delta Method

The delta method is the simplest, flexible and easy statistical downscaling method to use for variety of application. Also this method can generate large number of realization in order to assess uncertainty. This approach estimates the future climate variables by scaling the historical observed climate data in the reference period using a "delta value". This perturbation is calculated by comparing the observed and the simulated values for the different future scenarios. The reference period selected for the study comprises of the years from (1960-1990). This choice of range of years is justified by several reasons. The delta values obtained for each scenario have been calculated by averaging the value of each climate variable over the entire periods considered as shown below. Depending on the variable analyzed the delta value is calculated as a difference or a ratio. For temperatures (maximum and minimum), the perturbation is found by using a difference as expressed in equation (2). For the precipitation, the perturbation is presented as a ratio shown in equation (3).

$$\Delta Temperature = \overline{TMP}_{CRCM,future} - \overline{TMP}_{CRCM,reference\ period} \quad (2)$$

$$\Delta Precipitation = \frac{\overline{PCP}_{CRCM,future}}{\overline{PCP}_{CRCM,reference\ period}} \quad (3)$$

2.4.2 Quantile - Quantile method

This technique builds a correspondence between the output of CRCM and the observed data. This is a statistical downscaling technique, based on the bias correction approach. This method is described by [11] as a correction applied to the CRCM simulated data at the future, based on "a point wise daily constructed empirical cumulative distribution function".This method is used to infused or seasonal forecasts adjusting coarse-resolution with information of basin-scale for the flow of river Wood [12]. Advantage for this method that the downscaling refers can estimated for ensemble of climate models and emission scenarios, thereby characterizing the extent of uncertainty in the downscaled quantity. This technique proceeds in four steps [13]. First, observed large-scale atmospheric variables are chosen that offer the strongest and most plausible predictability of the local property of interest the variables. Process of screening can be follow by crossing correlation with the variables and the available predictors. Second, both the variables with selected predictor(s) of GCM are converting into quintiles with their respective 0^{th} to 100^{th} percentiles. The third , pairs of predictor variables percentiles are matched empirically by using analysis of regression. Future of local values can be derived from relationship of the same empirical scaling given the predictors of large scale for specified percentiles. In the present study, the QQ method is applied for precipitation.

3. Result and Discussions

3.1 Process Based Model

Climate data were collected for climate station located near Amqui, Quebec to develop a process based model to predict flows over study area watershed. The flow station for Matapedia River compiled data records were from 1982 to 2001 whereas the climate station compiled data from (1972 to 2006). Therefore; the process based model predicted flows from (1982 to 2001); however, the overlapping period for analysis is limited by the flow station .**Figure 3** illustrated that the model was able to predict and simulate the flow in study area watershed except the period between November 1995 to September 1996 which due to a missing data in flow station records. Also; it is clear that the extreme flood event happened between April to June which is due to snowmelt period and rain season in Matapedia river basin and the model was able to simulate .

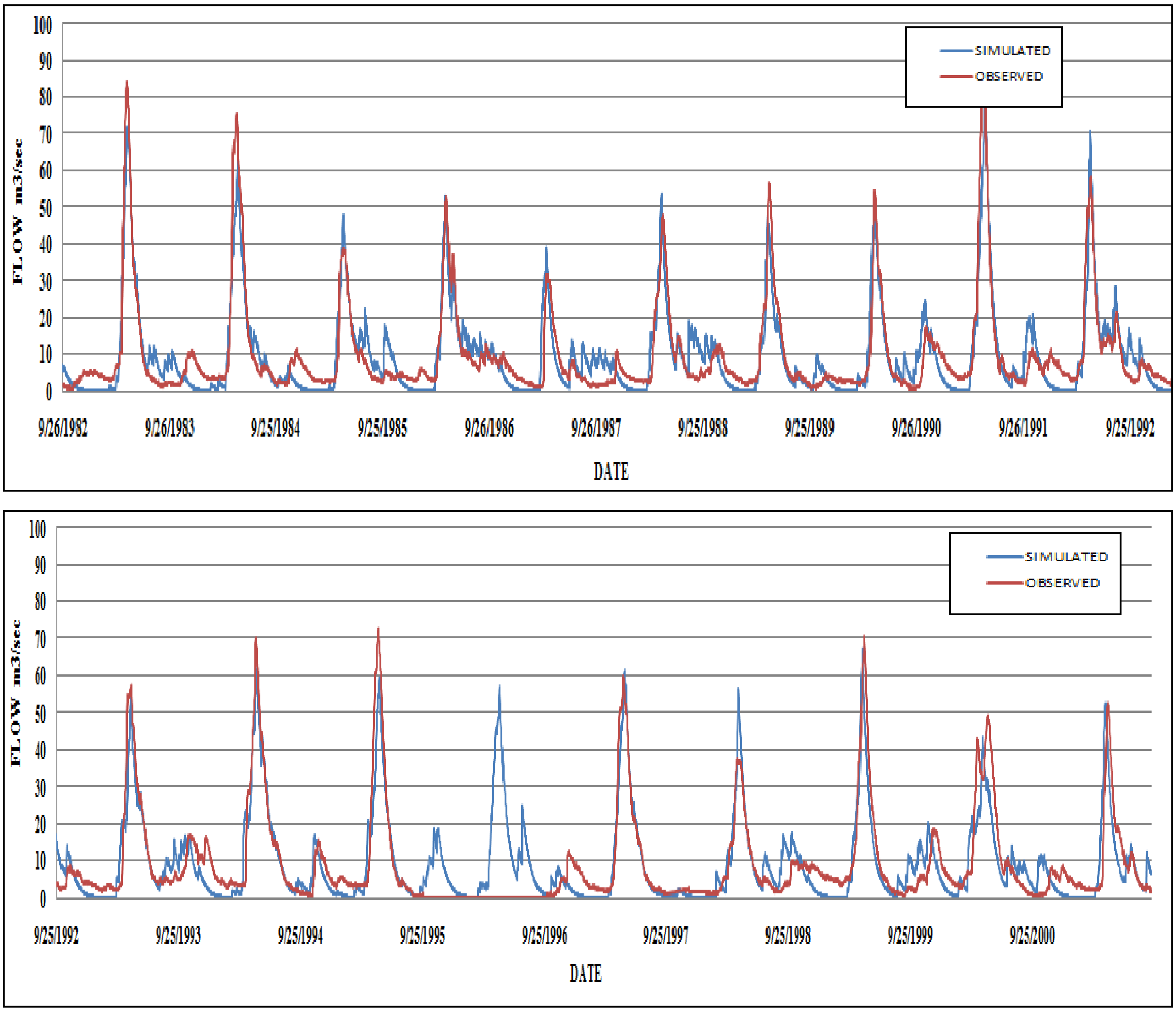
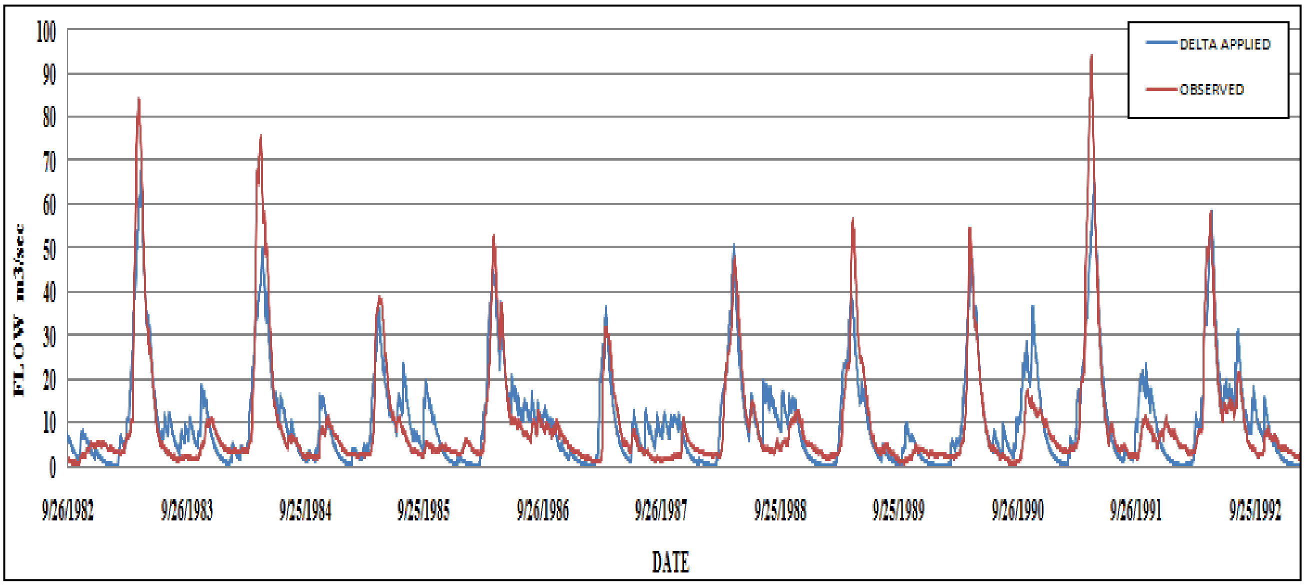


Figure 3. Process Based Model Simulation with Observed Records.

3.2 Delta Downscaling Method

In order to determine the impacts of climate change in Matapedia river basin the simple statistical downscaling method has been applied between current scenario which is the period between (1960-1990) and future scenario represented in the period between (2011-2100). Results shows that delta future increased in maximum and minimum temperature were (2.65 ^{o}C) and (3.02 ^{o}C) respectively whereas delta precipitation ratio in the future will be (1.038).Also; by applying those values to the watershed climate data and substitute it into process based hydrological model to adjusting the simulated model for future scenario; so future flow values shows an increased in the future low flows simulation , even though; the model appeared a decreased with an extreme flow peaks as shown in **Figure 4**. As a result there is a climate change impact on flow discharges and flood peaks in this watershed due to maximum and minimum temperature increasing in the future in addition to precipitation furthermore reference evapotranspiration (ET_o) average increased in future than current scenario about 14% .



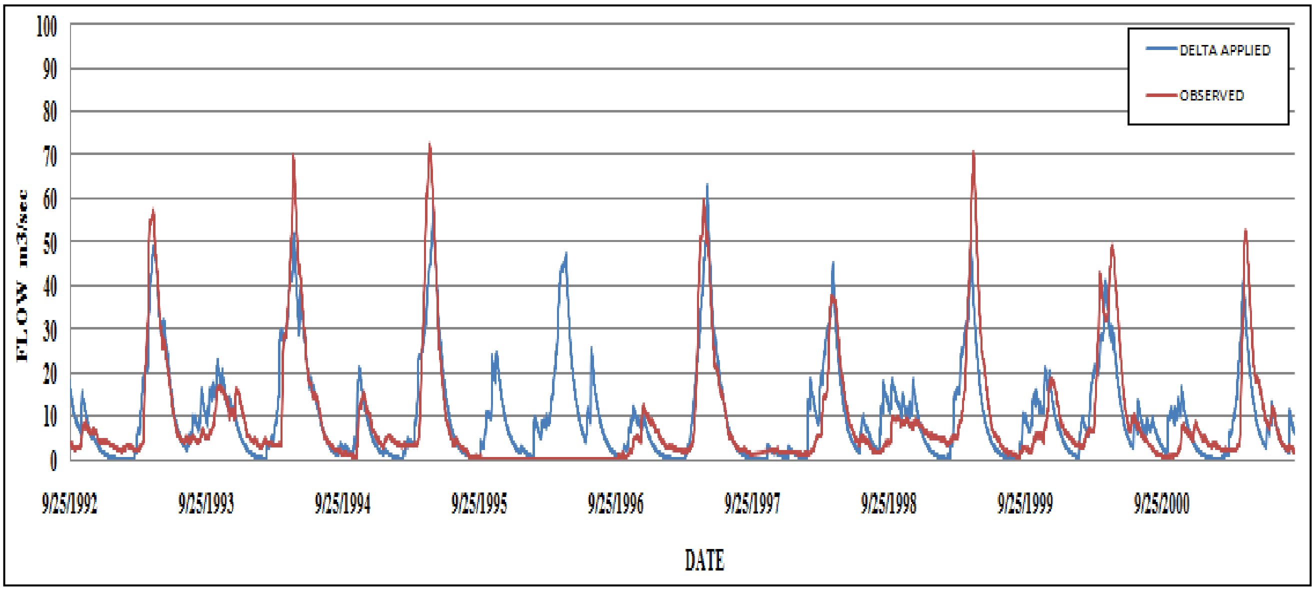


Figure 4. Process Based Model Simulation with Delta Downscaling Applied.

3.3 Quantile-Quantile Transformation

To compare the regional climate model with current precipitation (observed precipitation) distributions the Quantile-Quantile transformation was used to downscale global climate model output. This method is used to correct the distribution of the RCM output and builds a correspondence table between the magnitude of a simulated data and the true magnitude .**Figure 5** shows that RCM outputs have statistical distributions different from those of the observations which lead to a distortion of the simulated flows, and especially the extreme flows. Therefore; Quantile-Quantile method been used to correct such distortions and it is performed well, as shown in **Figure 6.** which is illustrated that the statistical distributions of the corrected RCM outputs are well reproduced and the probabilities of precipitation are

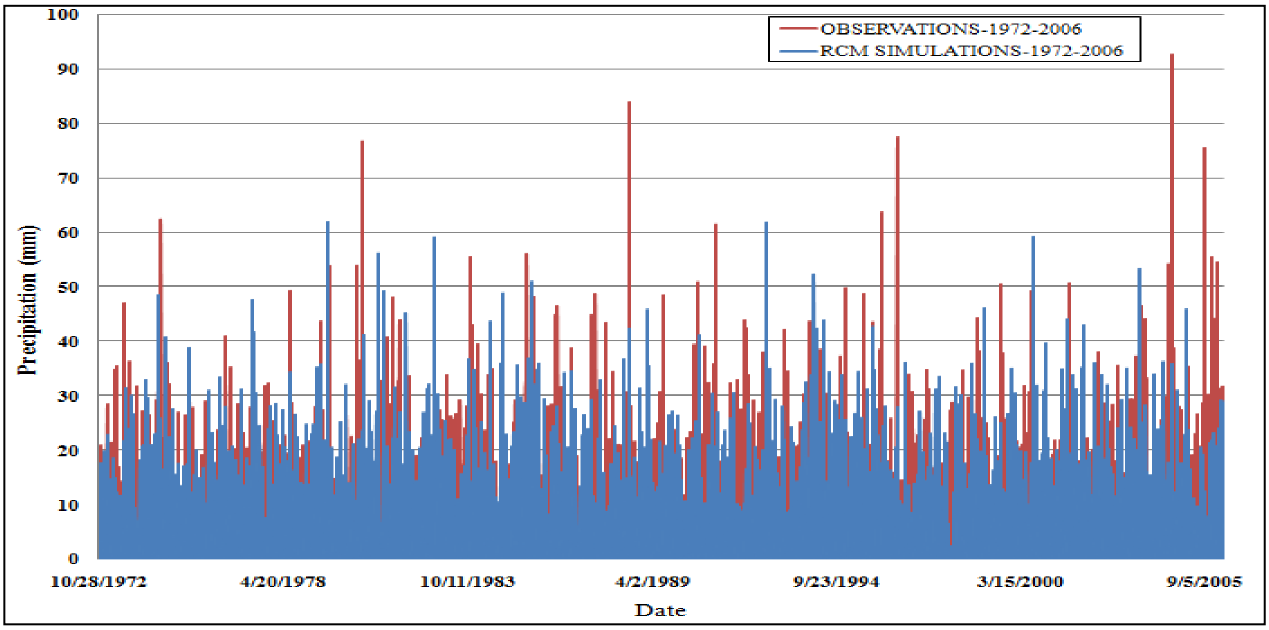


Figure 5. Observed Precipitation vs RCM Precipitation for Period (1972-2006).

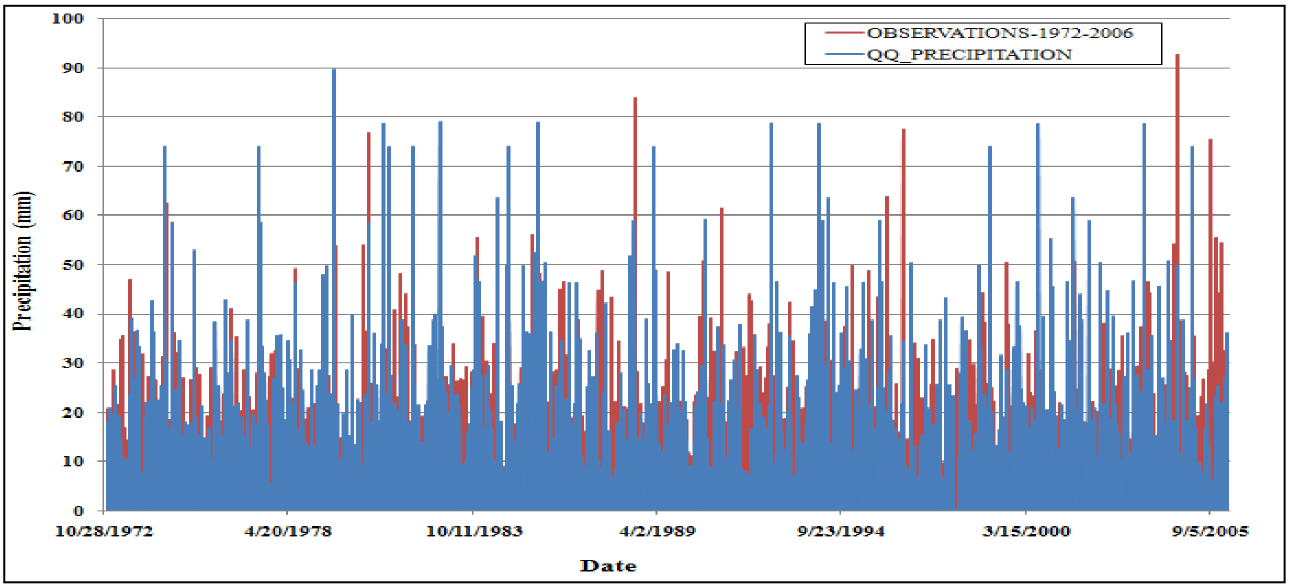


Figure 6. Observed Precipitation vs corrected Quantile-Quantile Precipitation for Period (1972-2006).

the same both for the observed and corrected RCM between observed and Q-Q precipitation even with extreme precipitation events. The statistical comparison of data distributions indicated that the median monthly precipitation of the future for 10 years low values is lower than the median monthly precipitation for current period for all months except month of June which is future slightly higher than current as shown in (**Figure7).** Moreover the watershed will experience a significant decrease in precipitation in all other months except April which slightly equal precipitation.

Whereas; analysis of the 100 and 1000 year extreme events illustrated in (**Figure 8**) which shows the predicted future 100 year extreme event will be higher than the predicted current 100 years extreme events during all months except July and August will be lower. This will impact floods on structural design and ecology through the watershed and should be planned for and managed to prevent negative impacts on the residents and environment. As same as the predicted future 1000 year extreme events gave a similar trend which is a median future higher than a median current in all months except January and July will be less as shown in Figure 8. Since most civil and environmental design is based on the 100 year events, mitigation strategies should

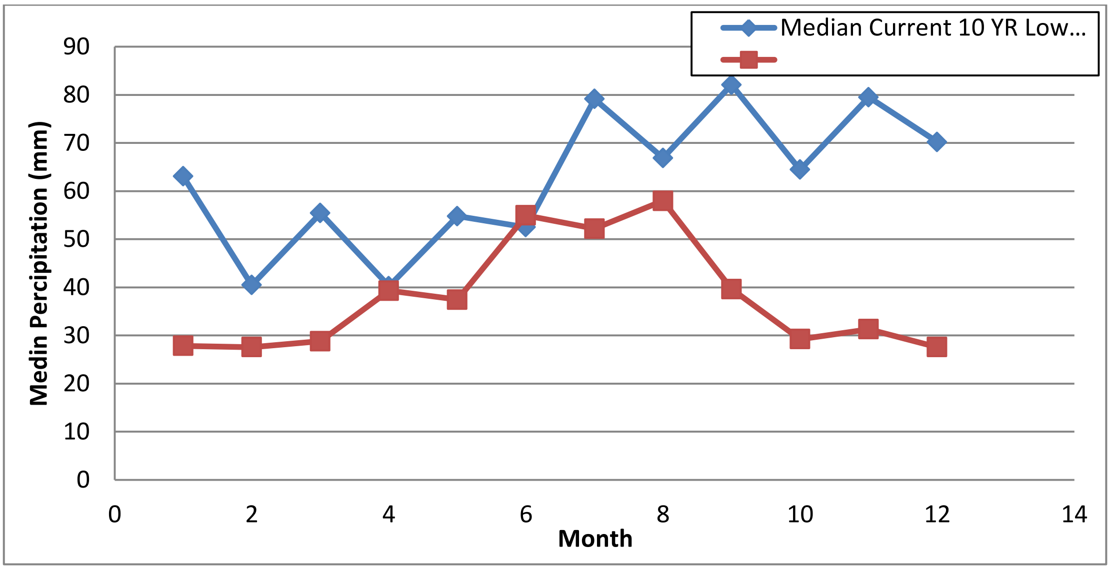


Figure 7. Median Precipitation for Current and Future Based on Quantile-Quantile Simulation.

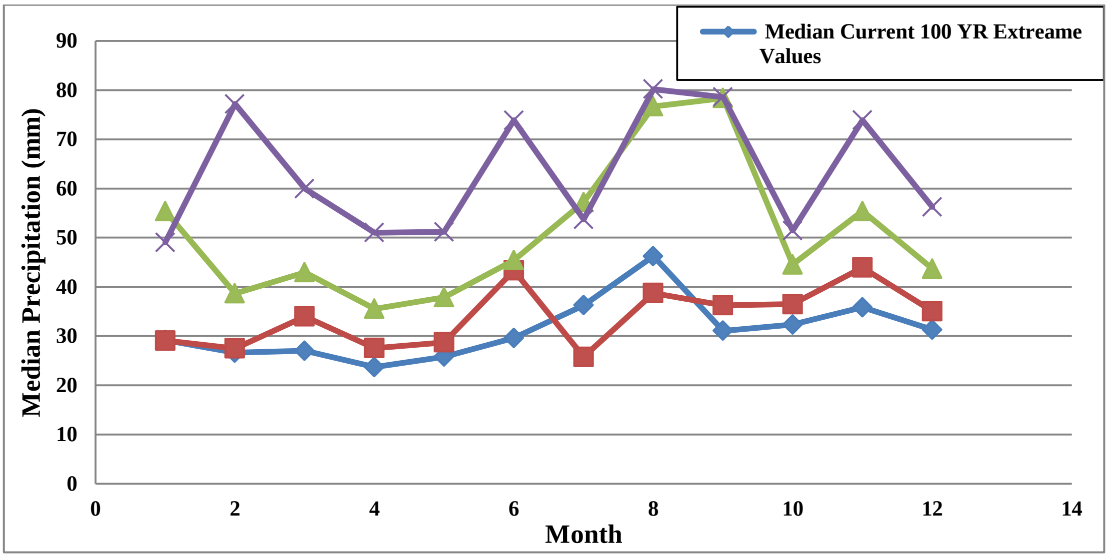


Figure 8. Median Precipitation for Current and Future Based on Quantile-Quantile Simulation for Extreme Events 100 and 1000 Years

proceed with caution in regards to the 1000 year events. Trend analysis shows the Matapedia river watershed, Quebec is subject to similar affects as the St. Lawrence tributaries in the future [5]. The hydrological effects associated with the temporal and precipitation effects are more prevalent in high flow events with an increase in mean annual discharge. Regions in Southwestern Quebec are expected to see same dramatic temperature increase of 3°C for maximum and minimum temperature increases, however, the same hydrological effects will be observed with increased winter discharge [4]. The application of the process based model created for this location would likely be statistically relevant for regions in Eastern Canada as they will have similar or easily modified parameters (soil characteristics, tree cover, etc.). From the analysis of this model, as well as others in Quebec, it is unlikely climate change will have a significant negative impact on the regions environment, social or economic system. Measures should be taken to account for the variation in snow fall as well as increased flows, however, simple mitigation strategies with infrastructure should allow for minimal effects.

4. Conclusion

Climate change became a progressive concern in the globe in last decades due to it is an impact on environmental, social and economic which is varies depending on site. The goal of this work was to find out the effect of climate change on the Matapedia river watershed, located in Quebec, Canada. A process based hydrological model was used to simulate the current and future hydrological scenario for the watershed using data obtained from CRCM and Environment Canada's hydrometric station database (HYDAT). Hydrological model gave a good result simulation for reference and future scenario and indicate a decrease future flow simulation especially with an extreme flow events discharges in the watershed. Downscaling using the delta method and quantile-quantile simulation showed climate change will have an effect on the watershed with a predicted increase in temperature (2.65 ^{o}C to 3.02) for the period (2011 to 2100). Moreover delta precipitation ratio will be (1.038) in the future for the same period simulation and median precipitations varying from month to month. Comparing the median current and median future precipitations indicated that the median monthly precipitation of the future for 10 years low values is lower than the median monthly precipitation for current period for all months except month of June which is future slightly higher than current. Likewise the watershed will experience a significant decrease in precipitation in all other months except April which slightly equal precipitation. Furthermore, the analysis for both the 100 and 1000 years extreme events shows all the months will have significant increases in precipitation except for the months of July and August for 100 years events will be lower, while; 1000 years events January and July will be less. This will impact floods on structural design and ecology through the watershed and should be planned for and managed to prevent negative impacts on the residents and environment. Furthermore, this model should be expanded to different regions in Canada and the northern United States to determine the sensitivity of localized models to decrease the over development of models.

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