Departement Aménagement et Environnement

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Identification of physical processes controlling spatial and temporal variation of river temperature

Rapport de stage présenté par Marceau COUDERT

Sous la direction de Madame le Professeur Jessica NEWLIN

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ABSTRACT

ENGLISH VERSION

Between 2014 and 2015, over sixty temperature data loggers were placed longitudinally along the centerline of the channel of the Susquehanna River, in the last 50 km of the West Branch before its confluence with the North Branch. The data loggers recorded temperature readings in fifteen-minute intervals and periodic collection of the logged data was attempted between 2014 and 2016. Thanks to this big collection of data, several river temperature models were created with the water quality analyses of HEC-RAS 5.0.3. The purpose of this study was to create the best river temperature model using temperature, meteorological and hydrological data. Methods of river temperature modelling are firstly explained and then two models with different types of input data are compared. Spatial analyses are made in order to compare model efficiency along the river. These analyses show that model accuracy is decreasing from upstream to downstream for both of them. Then temporal analyses were made and two different problems are observed. The first one is that two inexistent cooler temperature peaks are predicted by the model, and the second one is that accuracy tends to decrease over time. The first model, with a steady discharge and constant meteorological parameters, has an efficiency varying between 3% and 18% while the second model, with an unsteady discharge and variable meteorological parameters, has a better efficiency varying between 0% and 7%.

Keywords: River, temperature, modelling

FRENCH VERSION

Entre 2014 et 2015, plus de soixante enregistreurs de données de température ont été placés longitudinalement au centre de la rivière Susquehanna, dans les 50 derniers kilomètres du bras Ouest avant la confluence avec le bras Nord. Les enregistreurs de données ont enregistré des relevés de température toutes les quinze minutes et la collecte de données a été réalisée entre 2014 et 2016. Grâce à cette importante collecte de données, plusieurs modèles de température ont été créés grâce au logiciel HEC-RAS 5.0.3. Le but de cette étude était de créer le meilleur modèle de température en utilisant des données météorologiques et hydrologiques. Les méthodes de modélisation de la température de la rivière sont d'abord expliquées, puis deux modèles possedants différents types de données sont ensuite comparés. Des analyses spatiales sont effectuées afin de comparer l'efficacité des modèles le long de la rivière. Ces analyses montrent que la précision du modèle diminue d'amont en aval pour les deux modèles. Ensuite, des analyses temporelles ont été effectuées et deux problèmes différents ont été observés. Premièrement, le modèle prédit deux pics de basses temperatures inexistants lors des observation et deuxièmement, l'exactitude du modèle tend à diminuer avec le temps. Le premier modèle, avec un débit constant et des paramètres météorologiques constants, a une précision variant de 3% à 18% tandis que le second, avec un débit variable et des paramètres météorologiques variables, a une précision variant de 0% à 7%.

Mots clés : Rivière, température, modélisation

TABLE OF CONTENT

INTRODUCTION

River temperature has a major influence on the biological, chemical and physical processes in aquatic environments. Climate change will alter the temperature of rivers and this should pose problems by altering water quality and disrupting ecosystems. Therefore, a better understanding of the factors contributing to the spatio-temporal variability of river temperature is needed. Collecting data with temperature data loggers is a good way to begin to understand this problem. However, data cannot be collected in all locations. Stream temperature models offer a valuable secondary means to estimate this spatio-temporal variability of river temperature and they can provide a way to forecast expected changes in river temperature. Thanks to river temperature models, it is possible to complete missing temperature data in archives or even to improve their resolution. They can also predict temperature variations of a river and therefore help to better address the issue of climate change.

The Susquehanna River is the longest river on the East Coast of the United States (approximately 715km long) and it is the largest contributor of freshwater to the Chesapeake Bay. Therefore, its quality has a major influence on the Bay's health and productivity but also on all aquatic fauna and flora. Due to its size and importance, the quality of this river requires special attention. West Branch of the Susquehanna River has a very large amount of water temperature data in the last 50 km before its confluence with the North Branch since data loggers recorded temperature data every 15 minutes between 2014 and 2016. The creation of a river model in this area is therefore highly conceivable since the more data there are, the more accurate the model becomes. Nevertheless, even if the collected data are abundant, the river temperature models are not perfect and have their own limitations. Indeed, since rivers are highly variable from a physical and hydrological point of view, it remains very difficult to predict water temperature variations.

This study therefore focuses on the creation of a water temperature model on part of the West Branch of the Susquehanna River. After briefly presenting the methodological of river temperature model creation with HEC-RAS 5.0.3, it will try to analyze this model, understand its weaknesses and then improve its accuracy. Understanding the strengths and weaknesses of the model in simulating observed temperatures can help to identify important physical controls on the river temperature.

1. PRESENTATION OF THE HOST UNIVERSITY AND THE STUDY SYSTEM – CONTEXT

1.1 Bucknell University

Founded in 1846, Bucknell (Figure 1) is a private University in Lewisburg, Pennsylvania in United States (Figures 2 and 3). The University consists of the College of Arts and Sciences, the College of Management and the College of Engineering.

The College of Engineering is composed of six departments (biomedical engineering, chemical engineering, civil and environmental engineering, computer science, electrical and computer engineering and mechanical engineering) situated mainly in the Dana Engineering building.

The Department of Civil and Environmental Engineering, in which the internship takes place, aims to design, construct and operate systems that protect the environment, water resources, and human health.

***Figure 1**. Bucknell University (Source: Bucknell University on LinkedIn)*

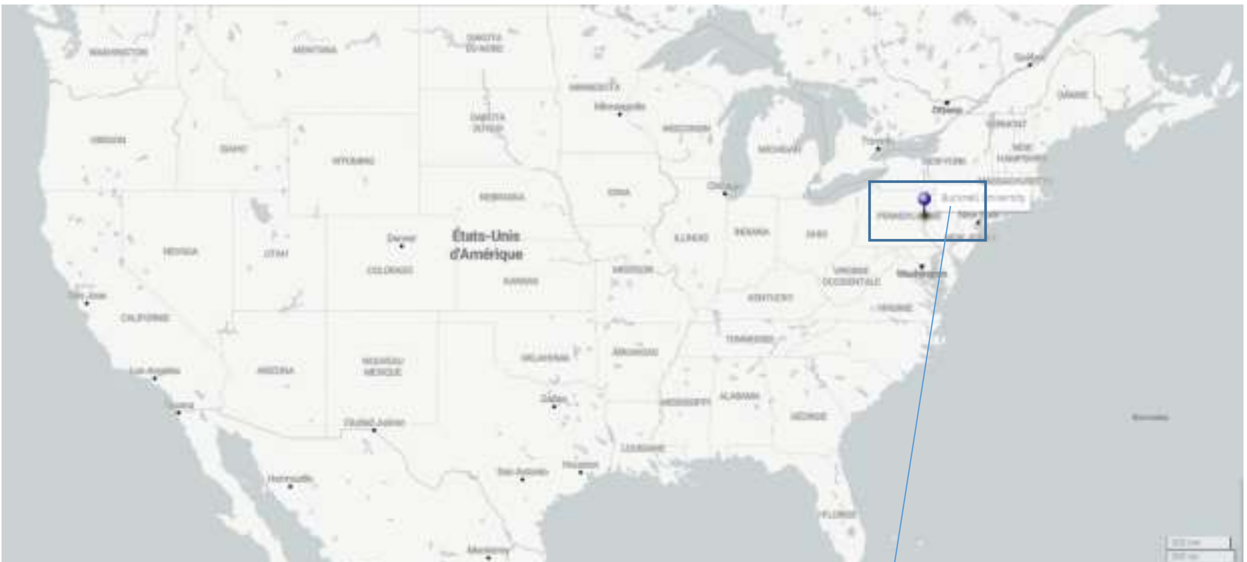


Figure 2. *Location of Bucknell University in United States*

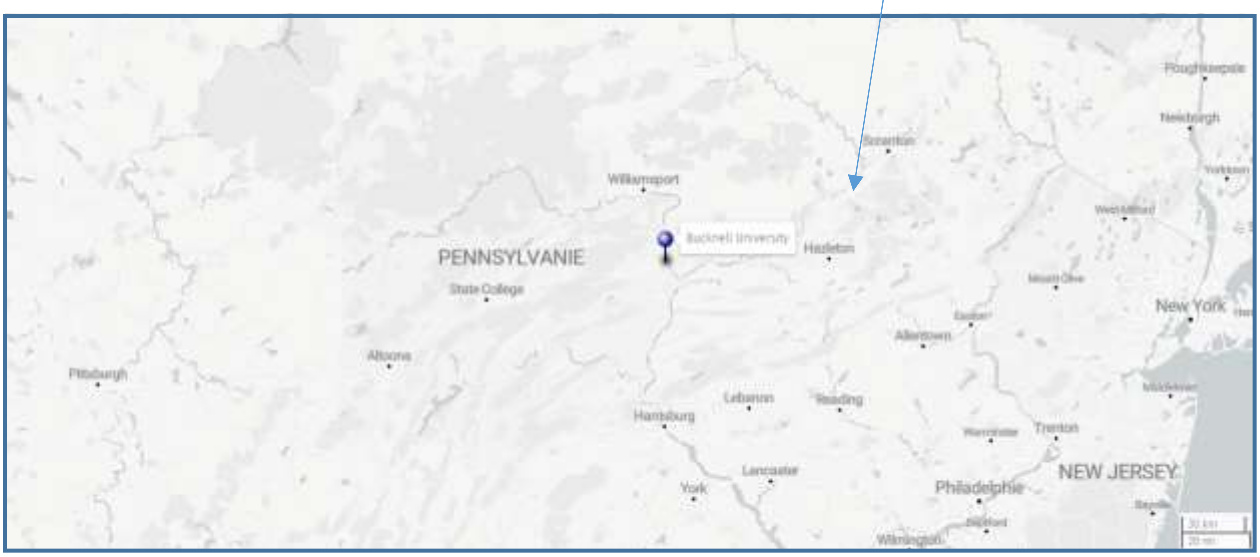


Figure 3. *Location of Bucknell University in Pennsylvania*

1.2 The Susquehanna River

About 715 km long, the Susquehanna River is the longest river on the east coast of the United States. It is divided into two upstream branches, a northern branch that originates in New York State and is often considered as the main branch and a shorter western branch that originates in the western part of Pennsylvania. Both branches confluence near Sunbury, in central Pennsylvania. The Susquehanna River Basin covers an area of 71,225 km2, covering almost half the area of Pennsylvania and parts of the states of New York and Maryland (Figure 4). This basin includes parts of the Allegheny Plateau region in the Appalachian Mountains. The river flows into the north of Chesapeake Bay, providing half of the influx of fresh water for the entire bay.

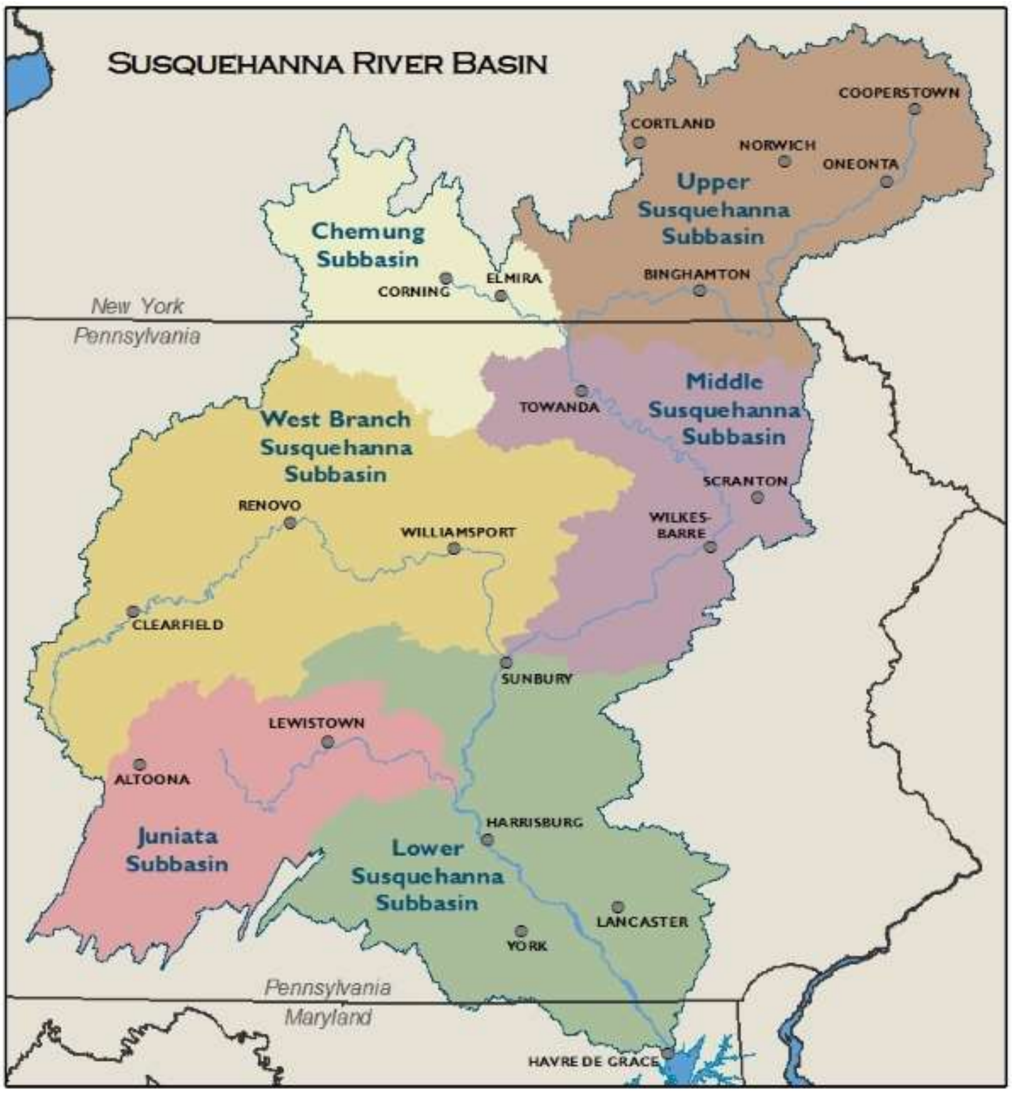
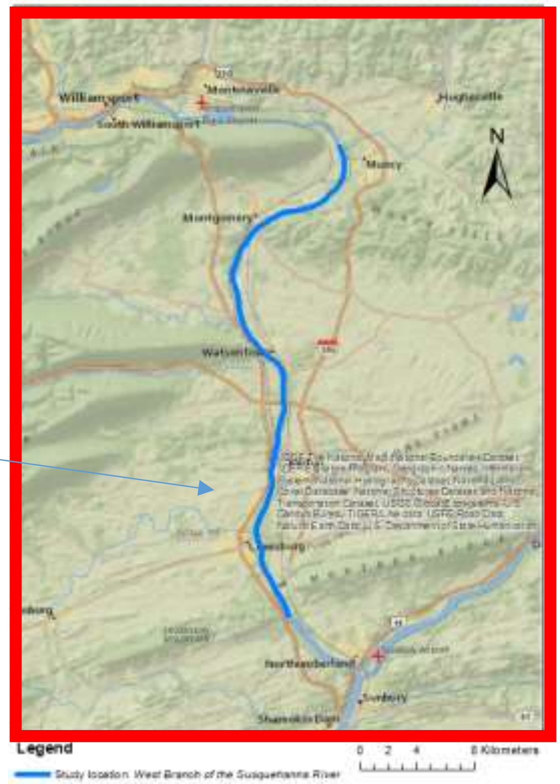


Figure 4. *Susquehanna River Basin (Source: Susquehanna River Basin Commission)*

1.3 Study area

The study takes place in the last 50 km of the West Branch of the Susquehanna River before its confluence with the North Branch. The river flows approximately north-to-south and is slightly meandering (Figure 5).

Figures 5a. *Study location in the Susquehanna River Basin*



Figures 5b. *Study location (made on ArcMap 10.5.1)*

Figures 5c. *Confluence of the West Branch with the North Branch of the Susquehanna River (Source: Marceau Coudert)*

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Data

Between 2014 and 2015, over sixty HOBO Pendant® temperature data loggers were placed longitudinally along the centerline of the channel of the West Branch of Susquehanna River (Figure 6). The spatial distribution of the data loggers was intended to capture the observed physical complexity of the river system; and in order to capture temporal variability of water temperature, the data loggers recorded temperature readings in fifteen-minute intervals. Periodic collection of the logged data was attempted between 2014 and 2016. In addition to the collected water temperature data, the data visualization and analysis makes use of weather parameters obtained from the Penn Valley Airport Observation site 14770 of the Quality Controlled Local Climatological Network maintained by the National Climatic Data Center, National Oceanic & Atmospheric Association, discharge available at U.S. Geological Survey gage sites, and field observations of the variability in the physical environment.

2.1.2 Software

In order to model spatial and temporal variation of river temperature, several software have been used. Excel was used in order to manage data and then to gather the useful ones. ArcMap 10.5.1 was use to observe data and to highlight some observations. It was also useful to process geomorphological data and then get the geometric data needful for the hydraulic modeling. HEC-RAS 5.0.3 allowed the realization of the temperature model taking into account meteorological, geomorphological and flow data.

Figure 6. *Temperature sensors location (made on ArcMap 10.5.1)*

2.2 Methods

2.2.1 Modeling channel geometry: from ArcMap to HEC-RAS

To model the geometry of the West Branch of the Susquehanna River, a Digital Elevation Model (DEM) was imported into ArcMap (Figure 7). Then, using HEC-GeoRAS, an interface between ArcMap and HEC-RAS, all the necessary geometric data (banks, flow paths and cross sections) were created and added to the map (Figure 8). To get more precision, 128 cross sections were created along the river every 300 meters.

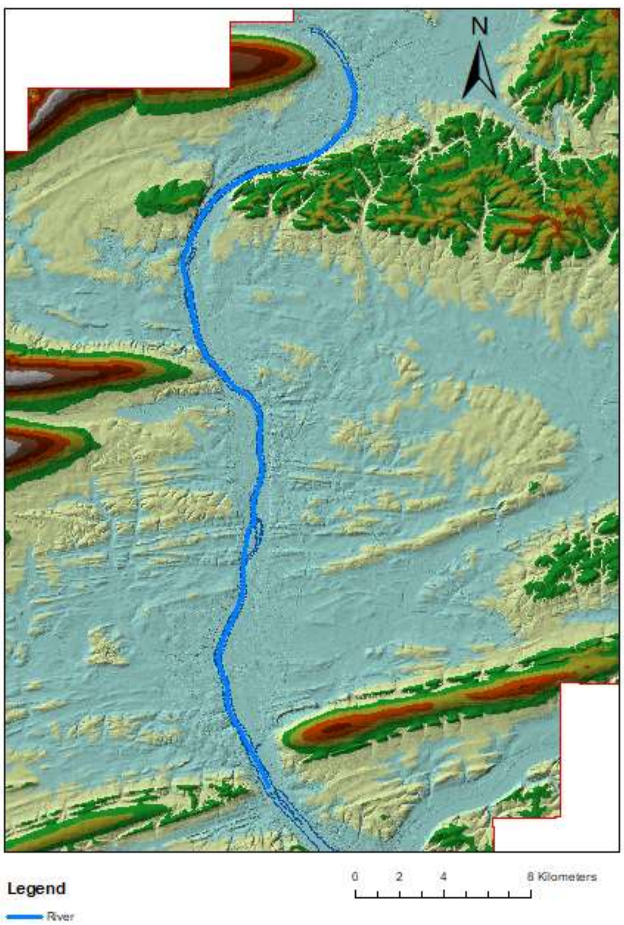


Figure 7. *Digital Elevation Model of the study location (made on ArcMap 10.5.1)*

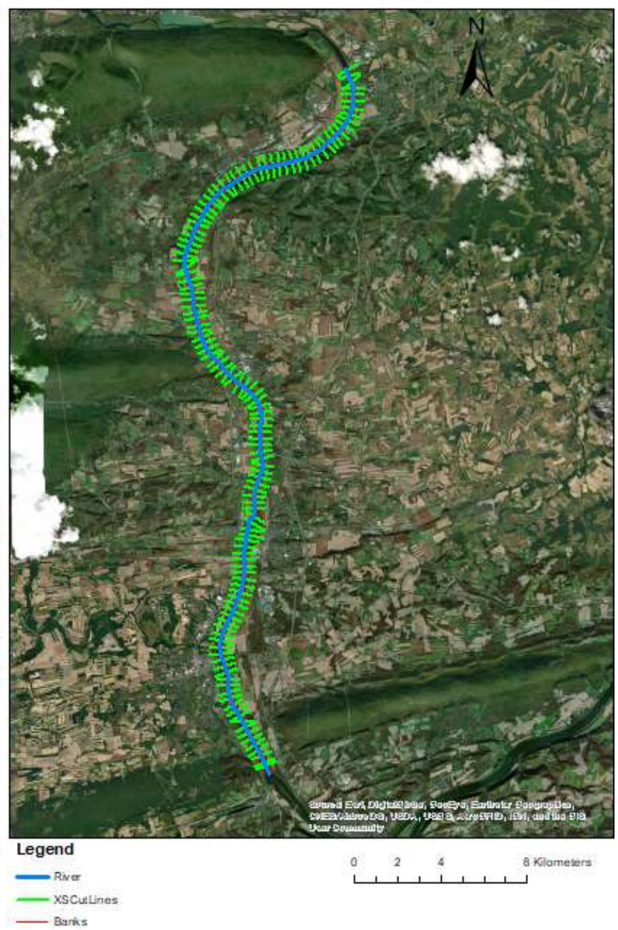


Figure 8. *Map of study location with all the necessary data for modeling (made on ArcMap 10.5.1)*

Manning's n values were fixed to 0.04 in the main channel and 0.065 on the left and right overbanks. Then, ArcMap geometric data were converted to HEC-RAS cross sections (Figure 9) in order to model flow behavior.

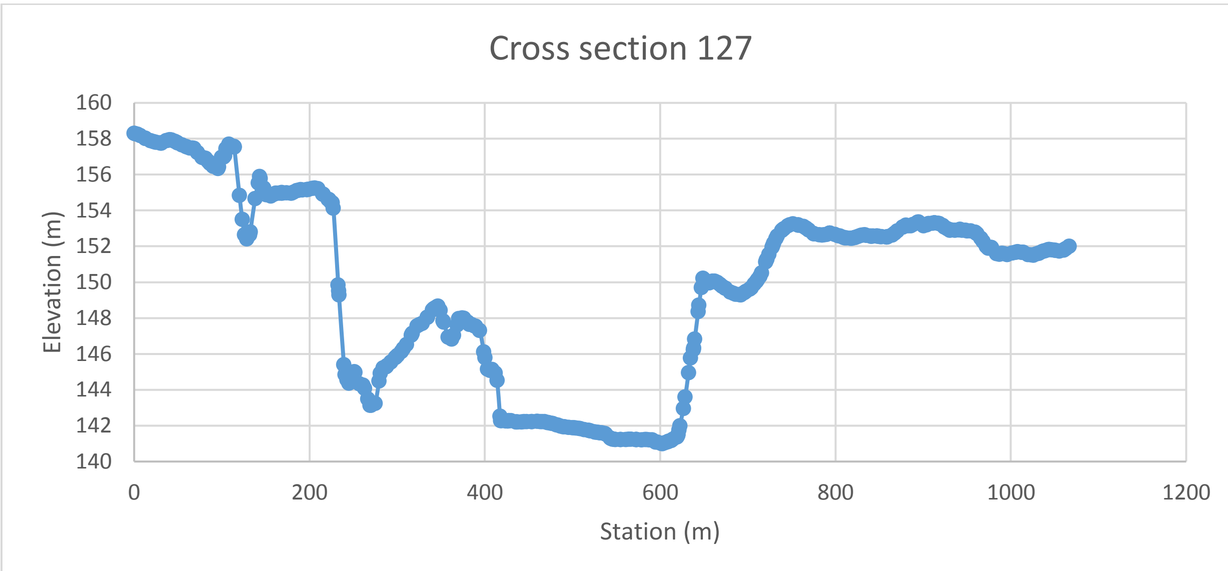


Figure 9. *Cross section 127 (data from HEC-RAS 5.0.3)*

2.2.2 Modelling unsteady flows

Variation of discharge has an effect on the variation of river water temperature. Therefore, to model the variation of river temperature, stream flows should be modeled as unsteady flow to be closer of reality.

This model run thanks to geomorphological data imported from ArcMap but also with hydrological conditions like discharge and Manning's n values that represents the roughness applied to the flow by the channel. To be functional, the flow model in HEC-RAS requires hydrological boundary conditions and initial conditions. Therefore, a flow hydrograph has been used as upstream boundary condition and another boundary condition that uses each flow value and computes the water level assuming uniform flow with the given bed slope (0.0002) has been used as downstream boundary conditions. For the initial condition, initial flow was fixed to 79m^3/s, the value of initial discharge in the river at the moment where model begin. All the hydrological data have been collected in the same period as temperature data collection and also in the same time interval (fifteen minute).

2.2.3Modelling temperature

To model river temperature in HEC-RAS 5.0.3, several data sets are required. The unsteady flow model was coupled with meteorological time series (solar radiation, air temperature, relative humidity, wind speed, cloudiness, and atmospheric pressure) and with water temperature time series. The river temperature time series were inputted at the upstream end and at the downstream end of the study reach. The model also requires initial conditions of water temperature at different cross sections of the river (US Army Corps of Engineers, 2016). For this model, five initial conditions were specified. A dispersion coefficient is also required to run the model, it can be fixed or computed by HEC-RAS.

To calculate heat transport in the river, the model uses the following equations (US Army Corps of Engineers, 2016):

$$\text{Heat}_{\text{Source/Sink}} = \frac{q_{net}}{\rho_w C_{pw}} \frac{A_s}{V}$$

q_{net} = net heat flux at the air water interface (W m^{-2})
ρ_w = density of water (kg m^{-3})
C_{pw} = specific heat of water (J kg^{-1} C^{-1})
A_s = surface area of water quality cell (m^2)
V = volume of water quality cell (m^3)

Figure 10. *Equation of heat source (US Army Corps of Engineers, 2016)*

Net heat flux is computed as the sum of individual heat budget components:

$$q_{net} = q_{sw} + q_{atm} - q_b + q_h - q_\ell$$

q_{sw} = solar radiation (W m^{-2})
q_{atm} = atmospheric (downwelling) longwave radiation (W m^{-2})
q_b = back (upwelling) longwave radiation (W m^{-2})
q_h = sensible heat (W m^{-2})
q_l = latent heat (W m^{-2})

Figure 11. *Equation of net heat flux (US Army Corps of Engineers, 2016)*

Solar radiation is computed from imported meteorological data like cloudiness, air temperature, and pressure but also with the site location (latitude and longitude) and elevation. The atmospheric long wave radiation is computed from input cloudiness and air temperature data. The back longwave radiation is computed from emissivity of water and from computed temperature value from previous time step. The sensible heat and latent heat are computed from input information on atmospheric pressure, air temperature, wind speed, water temperature and pressure.

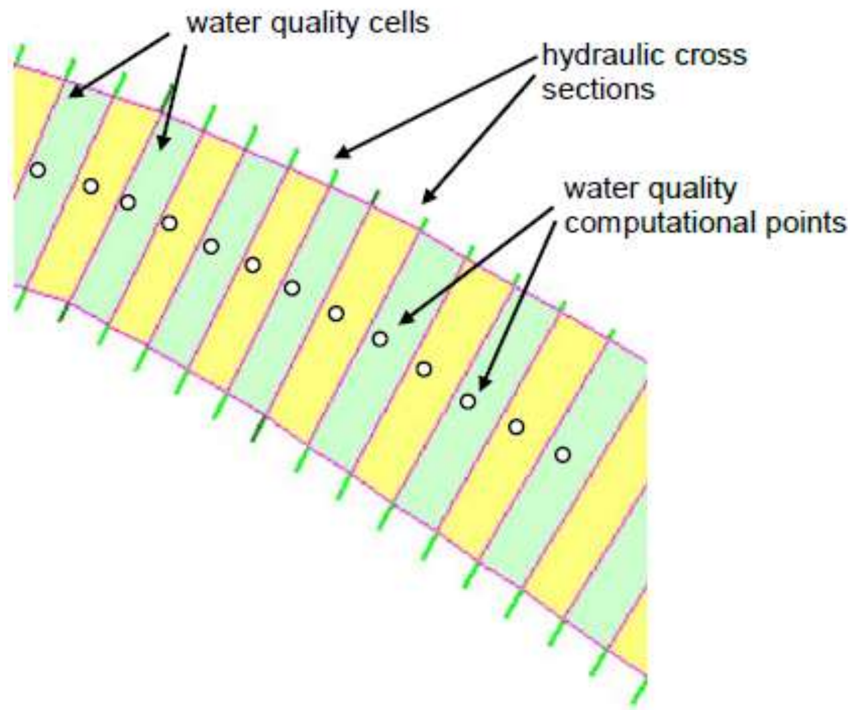


Figure 12. *Water quality cell configuration (from HEC-RAS User's Manual)*

All these equations are applied to water quality cells that are established between cross section by HEC-RAS. Water quality computational points are located exactly between cross section pairs (Figure 12).

3. RESULTS

In order to obtain the closest model to reality, several models were created with the same geometry and flow but with different meteorological input data and different periods of time. In this study, two models have been retained for comparison.

3.1 First model: steady discharge and constant meteorological parameters 8/08/14-8/29/14

First model ran for a period of nearly two months (from 08/08/14 to 08/29/14). This period was chosen because it was the one that had the most available river water temperature data.

This model was launched with fixed dispersion coefficient of 1.9m^2/s. The atmospheric pressure was fixed on 100.197 KPa (Appendix 1), which was the average of pressure data for the modeled time period. Air temperature, humidity, short wave radiation and wind speed (Appendix 1) were inputted with one average value per day in the modeled time period. Cloudiness (Appendix 1) was fixed with a constant value of 0.28 on a scale between 0 and 1 which was also the average value of the entire modeled time is period.

For simplicity, the model was first launched with a steady flow value representing the discharge average of the modelling period.

To determine the accuracy of model, error was calculated on several cross sections with the following equation:

Error = ABS$\left(\frac{\textbf{model value} - \textbf{observed value}}{\textbf{observed value}}\right)$.

A map of the accuracy (Figure 13) shows the error of the model along the river. The accuracy of the model is attenuated from upstream to downstream varying from 3% to 18% of error.

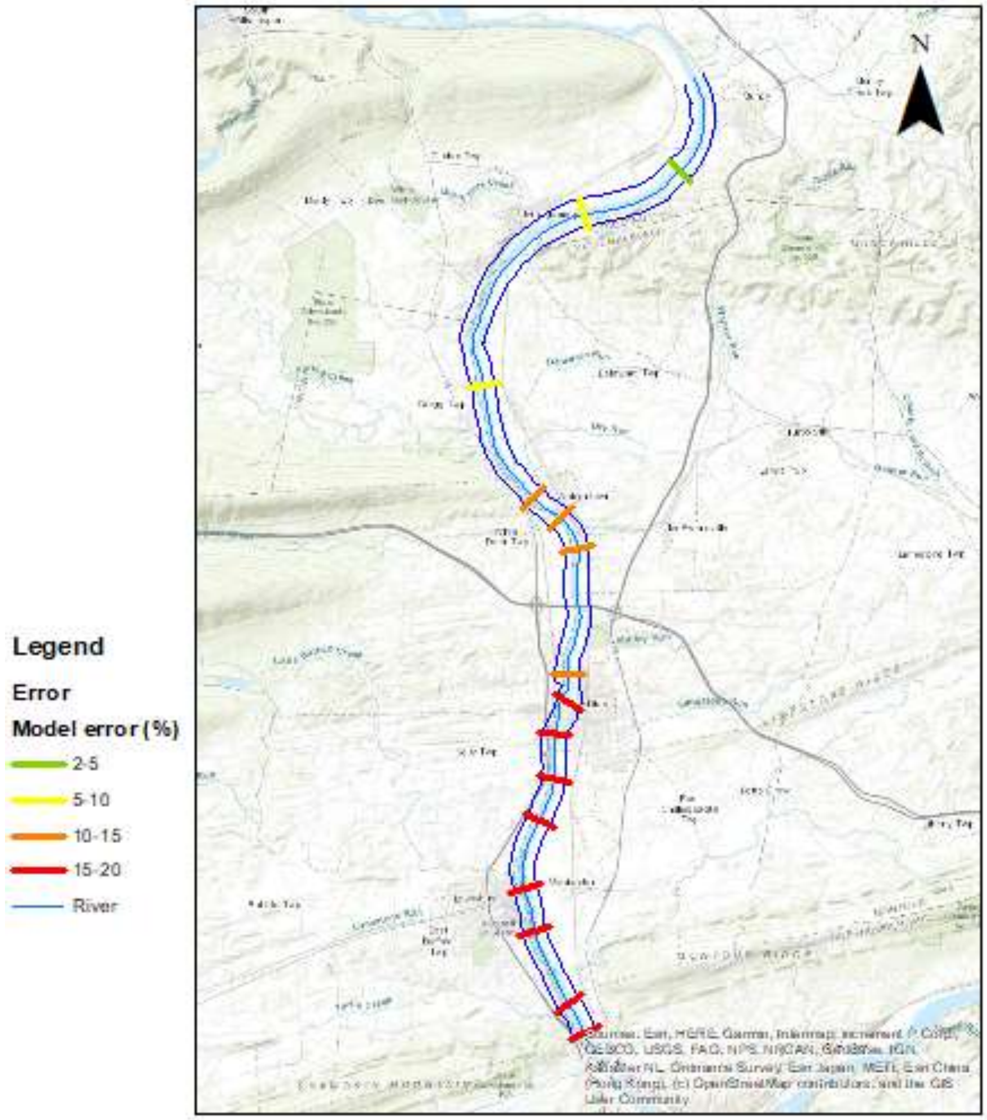


Figure 13. *Model error of the first model with steady flow (made on ArcMap 10.5.1)*

3.2 First model: unsteady discharge and constant meteorological parameters 8/08/14-8/29/14

Then, problem of discharge data importing was fixed by adjusting date and time format in order to get the good date format for HEC-RAS. Model was so launched with an unsteady flow model in order to get better results than the previous one.

Map of model error (Figure 14) was created in the same way as the previous one. It shows better results than the previous one, varying from 4% to 16% of error. But the same problem of efficiency decreasing from upstream to downstream still persists.

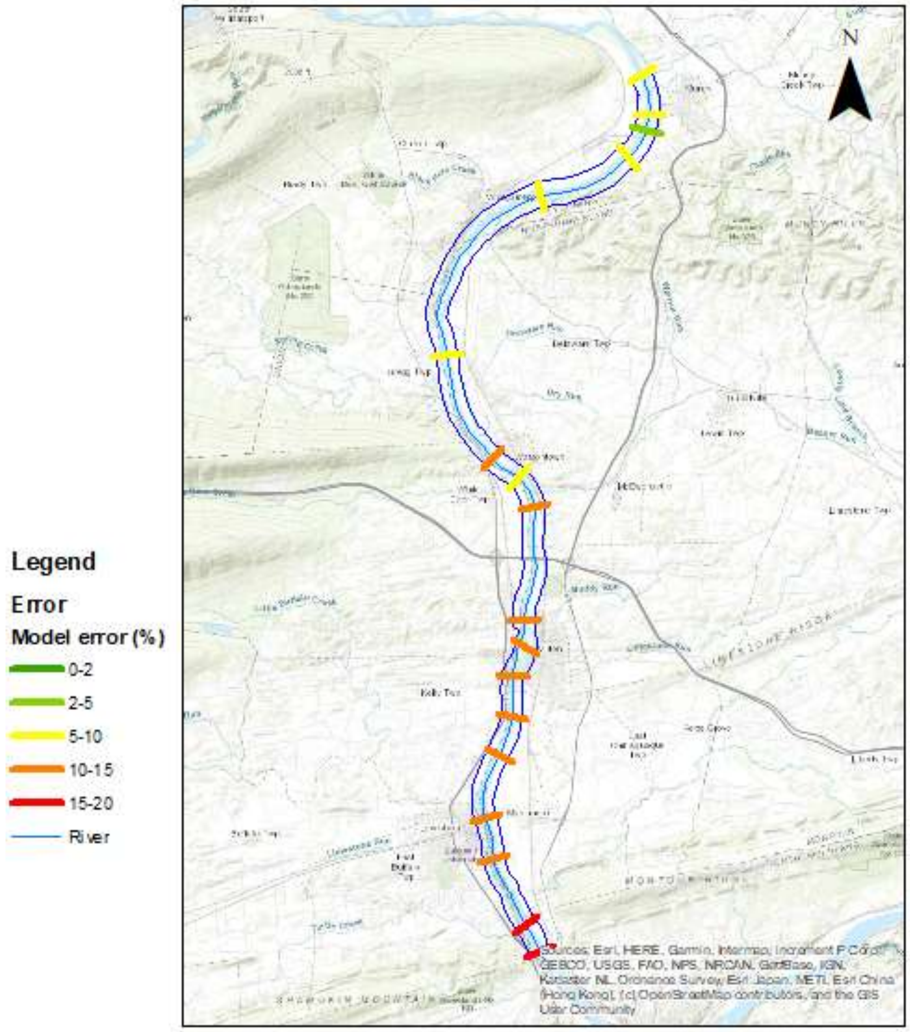


Figure 14. *Model error of the first model with unsteady flow (made on ArcMap 10.5.1)*

Figures 15 show variations of river temperature on two cross sections during the modelling period (from 08/08/14 to 08/29/14). The blue line represents observed temperature values and the orange one represents modeled temperature values. Therefore, the model results in cooler temperatures than the observed river water temperatures, and it also predicts two peaks of cooler temperature at the beginning of the period. These plots also show that temperature differences between observations and model increase over time.

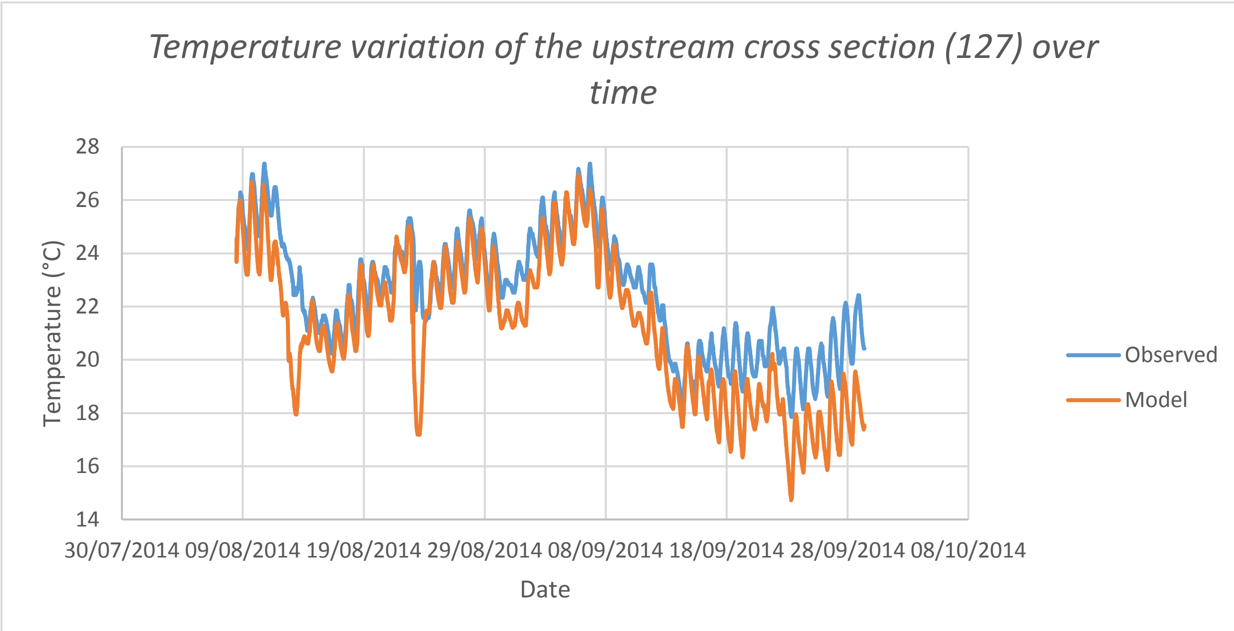


Figure 15a. *First model: Temperature variation of the upstream cross section over time (data from HEC-RAS 5.0.3)*

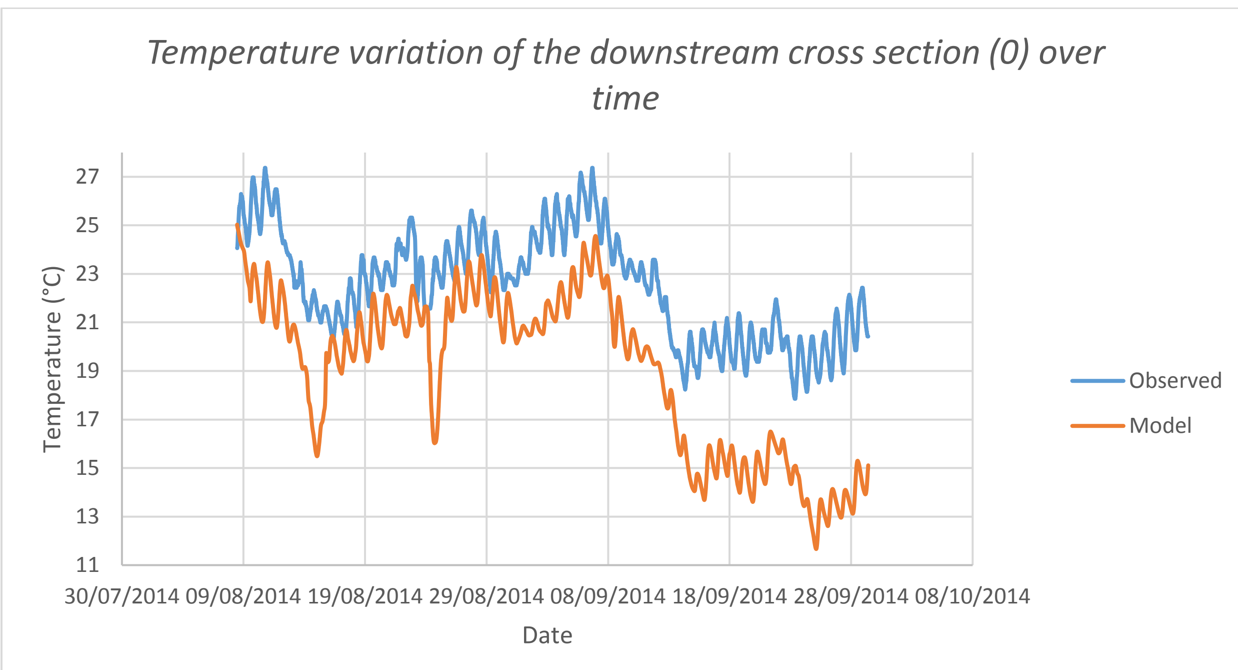


Figure 15b. *First model: Temperature variation of the downstream cross section over time (data from HEC-RAS 5.0.3)*

3.3 Second model: unsteady discharge and variable meteorological parameters 8/10/14-9/10/14

The second model was run for a period of one month (from 08/10/14 to 09/10/14). In order to get a better temperature model, meteorological input data were improved.

The model was launched with no constant value of required parameters. Dispersion coefficient and solar radiation (Appendices 2) were computed by HEC-RAS. All other parameters (Appendices 2) were obtained from the Penn Valley Airport Observation website and from the meteorological database of the Environmental Engineering Department of Bucknell University. When the time interval between data was variable, data were interpolated with MATLAB in order to have a constant 15-minute interval.

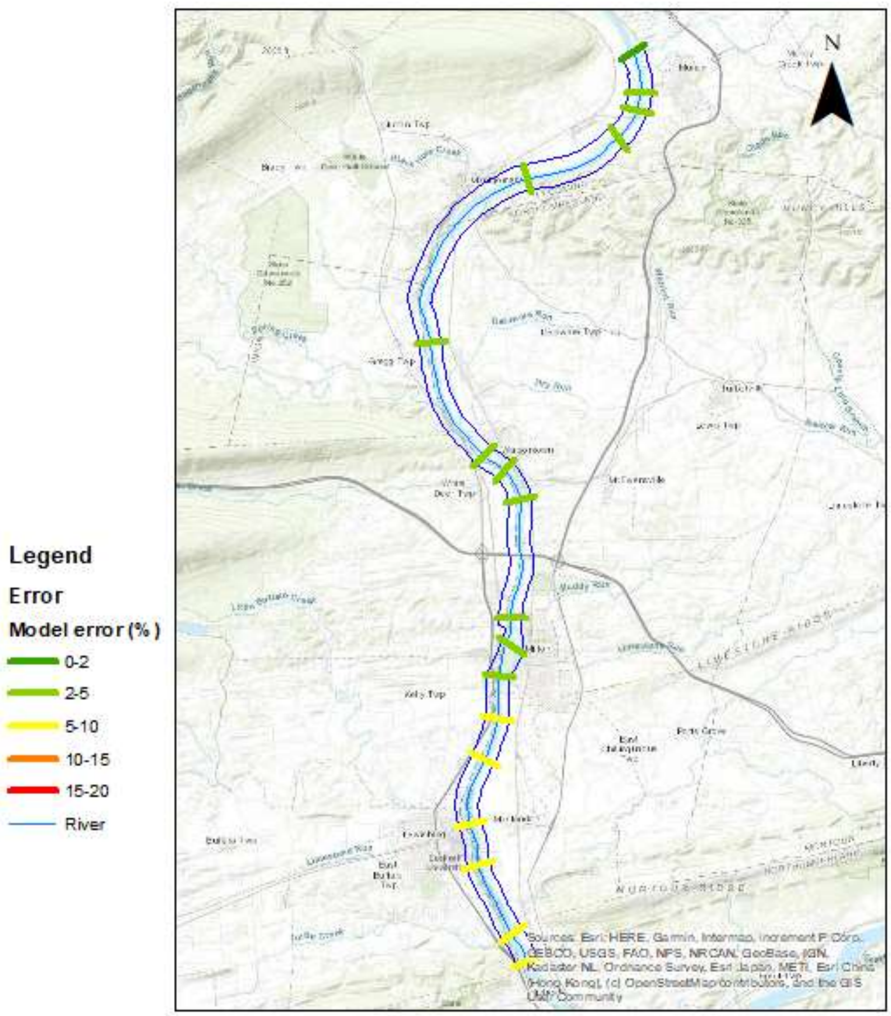


Figure 16. *Model error of the second model (made on ArcMap 10.5.1)*

This model gives good results of temperature predicting. Indeed, errors of each cross section vary between 0.16% upstream and 7.39% downstream. Problem of accuracy decreasing from upstream to downstream is attenuated but still persists (Figure 16).

Figure 17a shows that model (orange line) is very close of observed temperatures (blue line) at the upstream end. At the downstream end (Figure 17b), the model is moving away from observed temperature and predicts warmer temperatures. Model and observed data are both in-phase along the river.

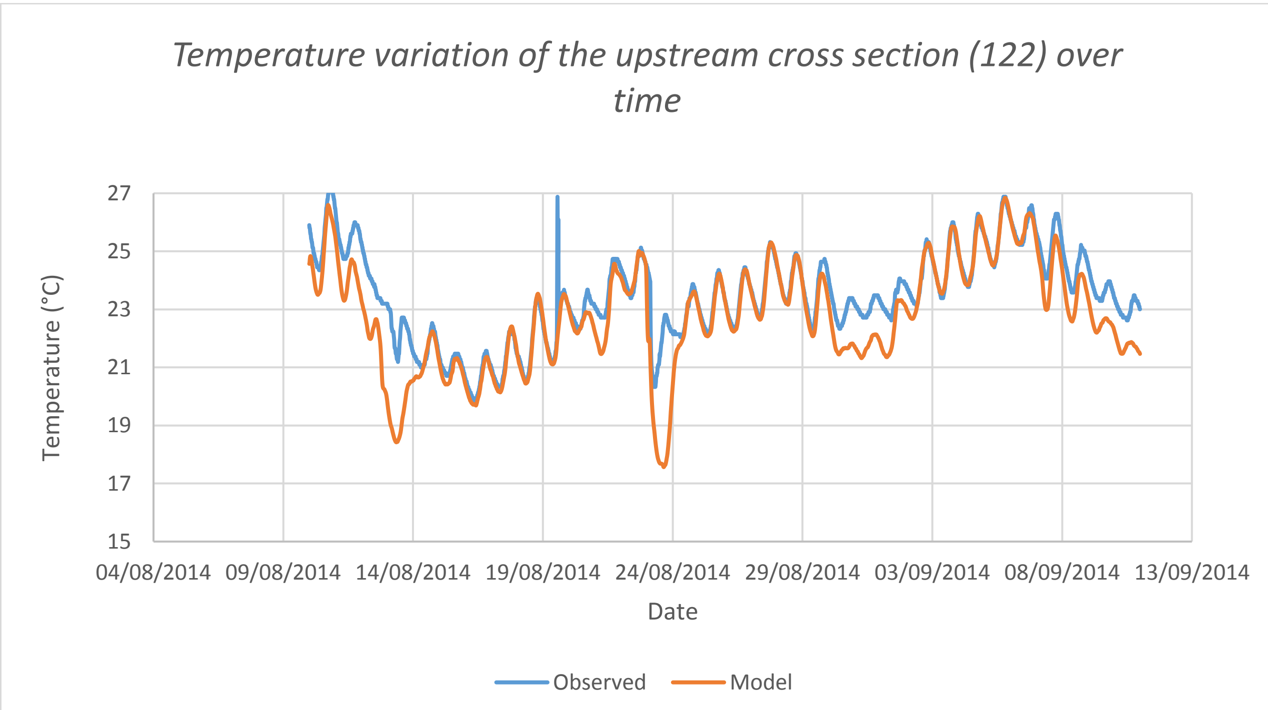


Figure 17a. *Second model: Temperature variation of the 122 cross section (upstream) over time (data from HEC-RAS 5.0.3)*

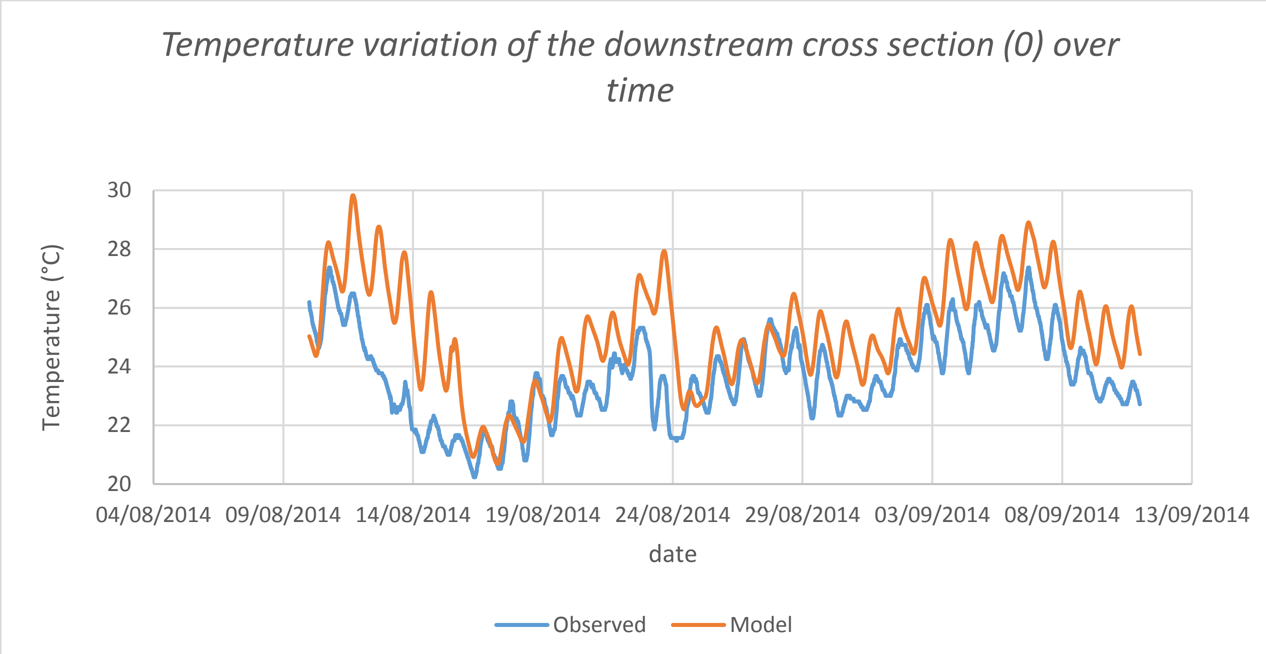


Figure 17b. *Second model: Temperature variation of the 0 cross section (downstream) over time (data from HEC-RAS 5.0.3)*

3.4 Comparison

In order to better figure out differences of efficiency between models, comparisons of error along the channel were made (Figure 19).

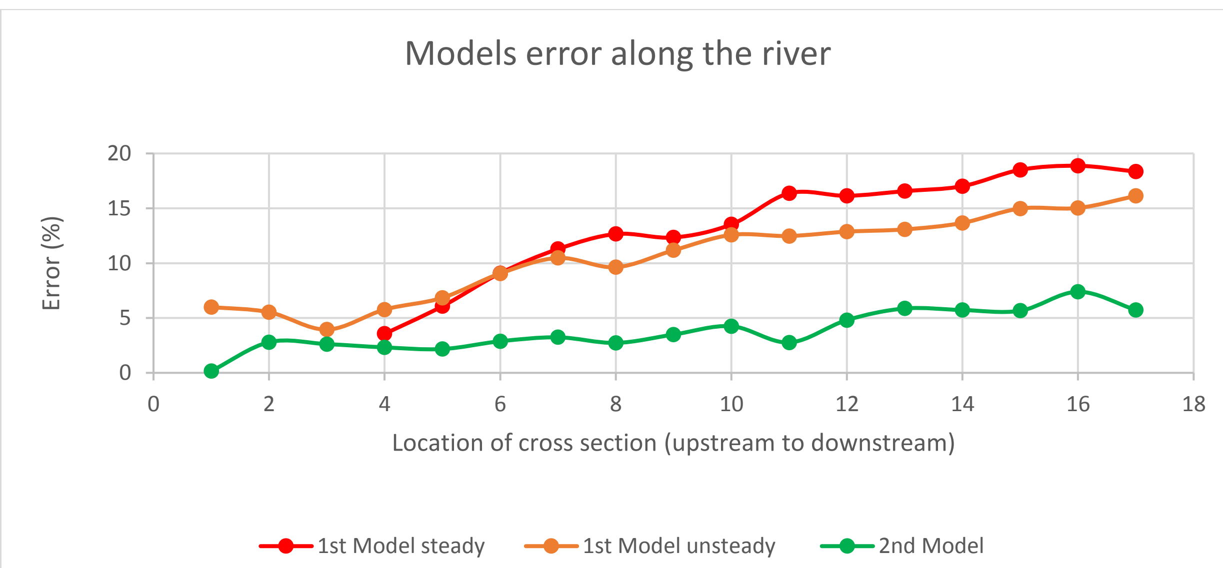


Figure 18. *Comparison of models error along the river*

4. DISCUSSION

To understand why model predicts those two peaks of cooler temperature, comparisons with others parameters were made. Difference between modelled and observed data was calculated for every temperature data over time and a plot of the model error was made (Figure 19). When this plot is compared with the hydrograph (Figure 19) of the study area on the same period, similarities emerge. Indeed, the model seems to have difficulty adapting to large variations in flow rate.

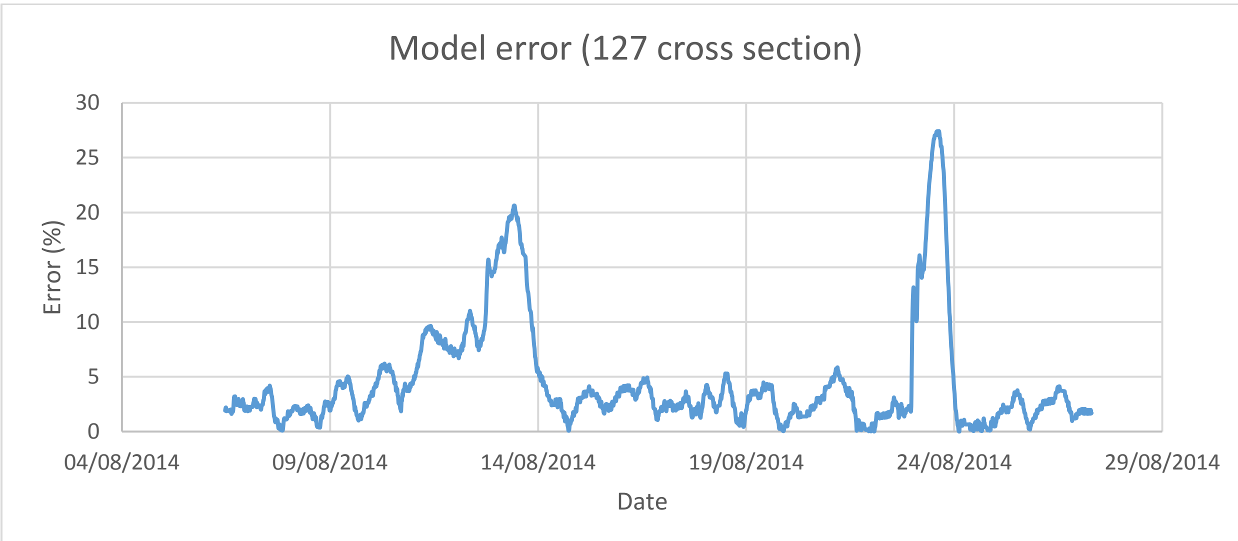


Figure 20. *Model error on the 127 cross section over time*

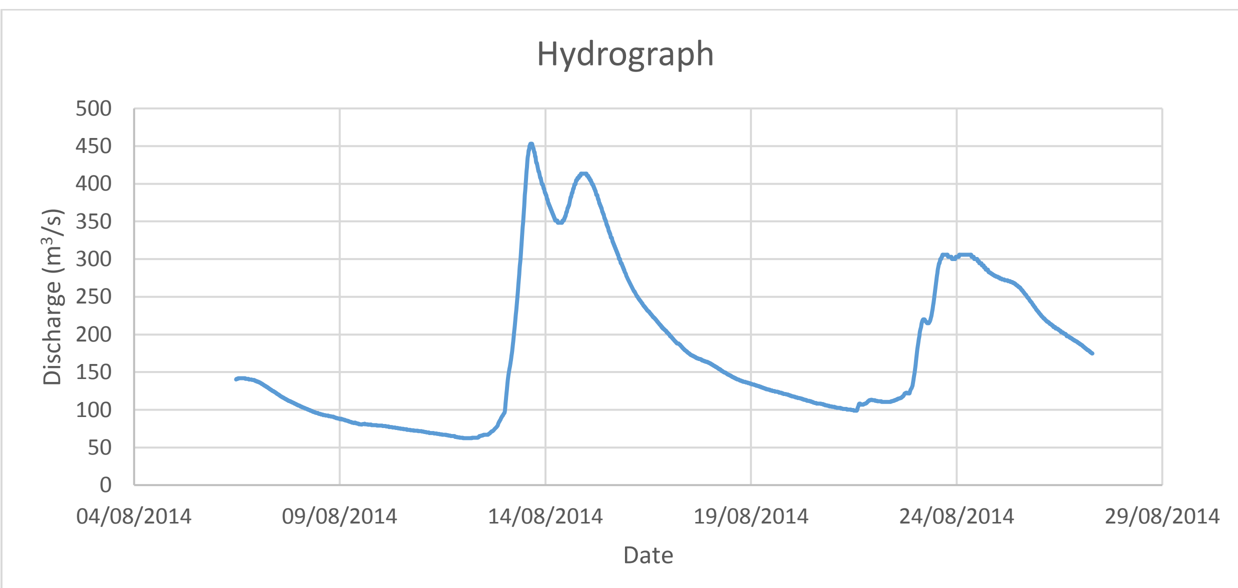


Figure 21. *Hydrograph of the study area*

Concerning the problem of efficiency decreasing from upstream to downstream, two hypothesis may be envisaged. This two hypothesis could come from a problem of flow model. Indeed, the unsteady flow model that allows the river temperature model to run has only one hydrograph for all the study area. This hydrograph comes from a downstream station and the river has many tributary streams along the study area that could modify river temperature. The second reason could come from groundwater effect. Indeed, these models do not take into account groundwater discharge and due to a lack of data, the input of this type of data is not possible. It would therefore be necessary to take into account temporal and spatial variations in the flow of the river.

CONCLUSION

The main purpose of this research was to build a river temperature model using morphological, meteorological and hydrological data. The morphological data of the river were obtained from a Digital Elevation Model (DEM) and then sent to the HEC-RAS software via HEC-GeoRAS. Weather data were obtained from the Penn Valley Airport Observation. Hydrological data were obtained from a database of the U.S. Geological Survey discharge gages on the West Branch of the Susquehanna River. The water temperature data used for this model came from temperature data loggers installed by the Bucknell University Department of Civil and Environmental Engineering.

Several models with different input data have been built and have given different results. The last one obtained gives good quality results since by running over a period of 1 month it is able to predict spatial and temporal temperature variations with a maximum error of only 7%. These results were obtained thanks to the large number of data present in this model. Nevertheless, the model has imperfections because it predicts inexistent temperature drops and its precision decreases in time and downstream longitudinal distance. These weaknesses are probably due to a lack of hydrological data like groundwater and tributaries discharge that are currently not included in the model.

This model can be further improved by adding the missing hydrological data and by performing a sensitivity analysis of each input parameter in order to understand their contribution to the estimation of water temperature variation. Once the model is finished, it could be used to complete the missing data from the temperature archives but also to predict temperature variations for the coming years. Thus, our understanding of hydrosytems improved and allows us to approach the problem of climate change with more capabilities.

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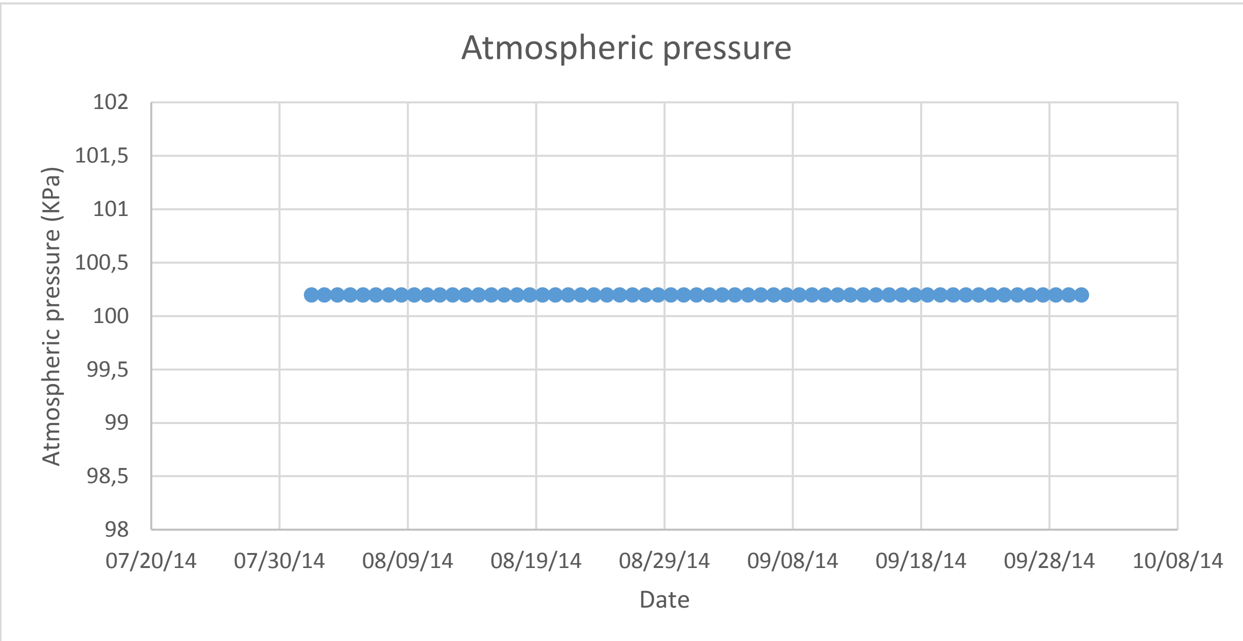
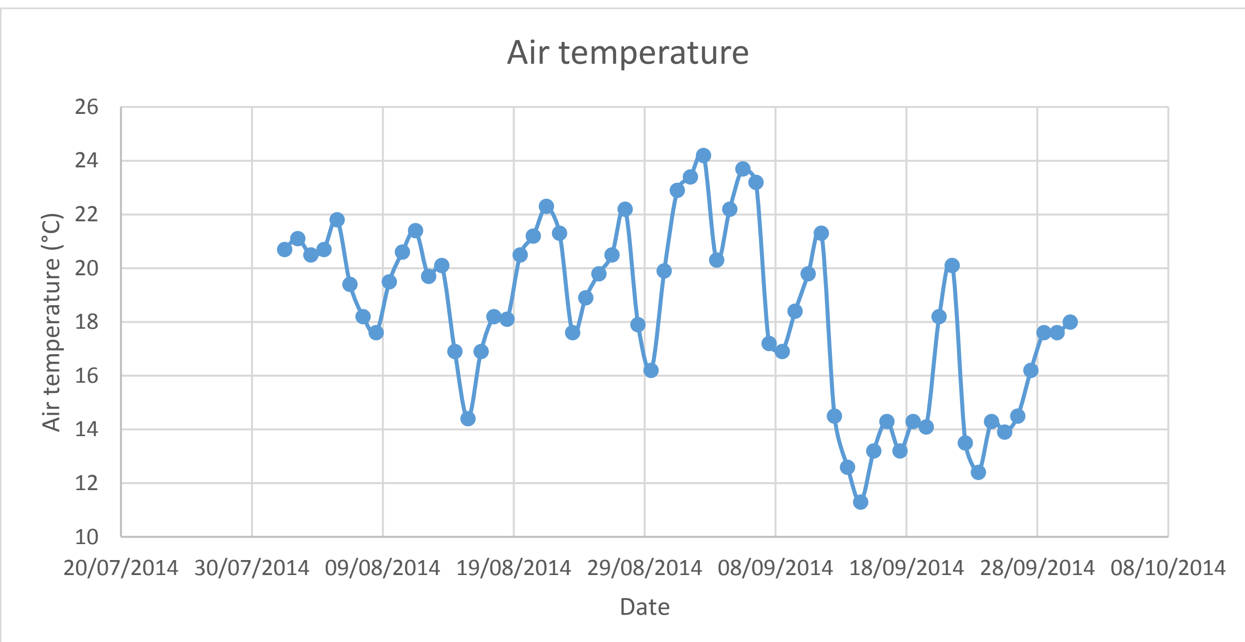
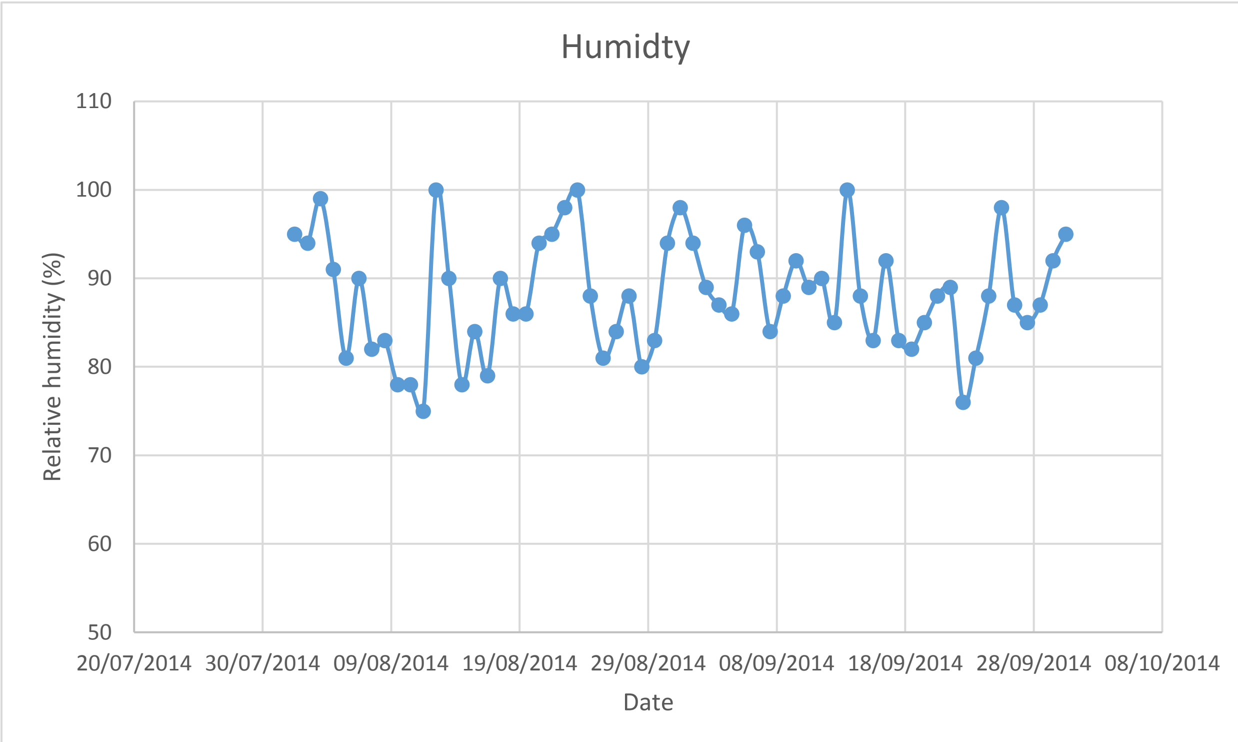
LIST OF THE FIGURES

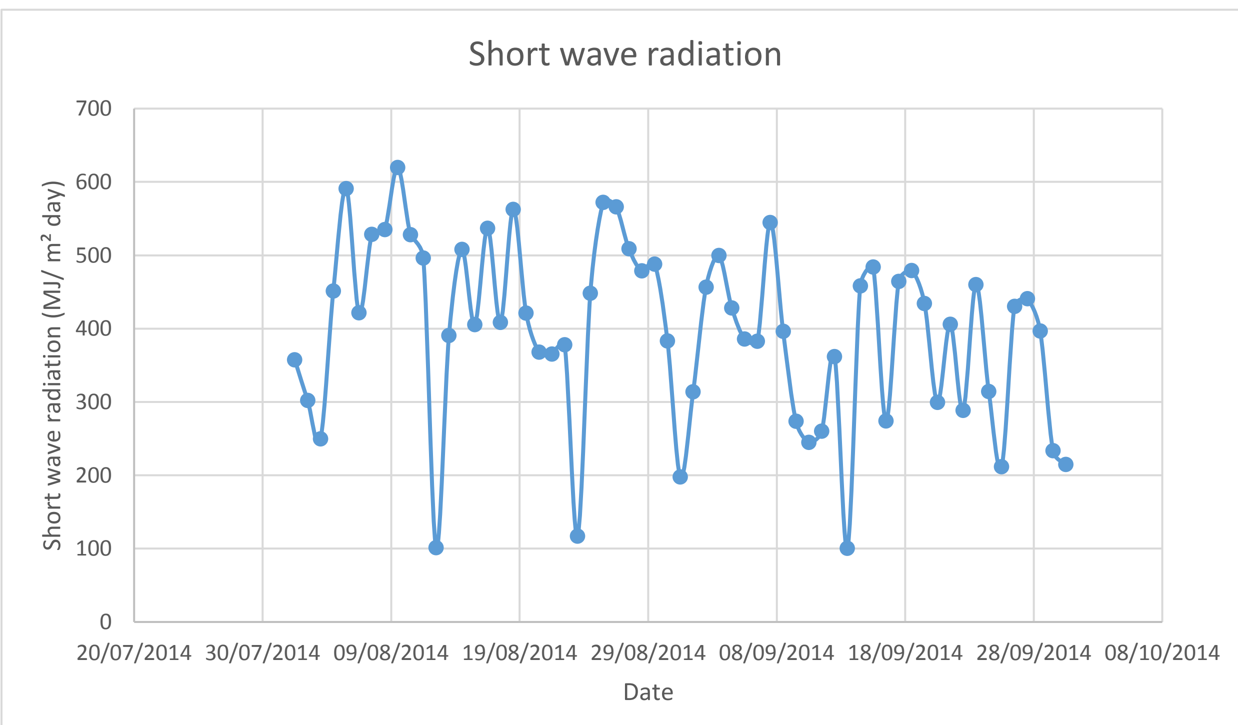
APPENDIX

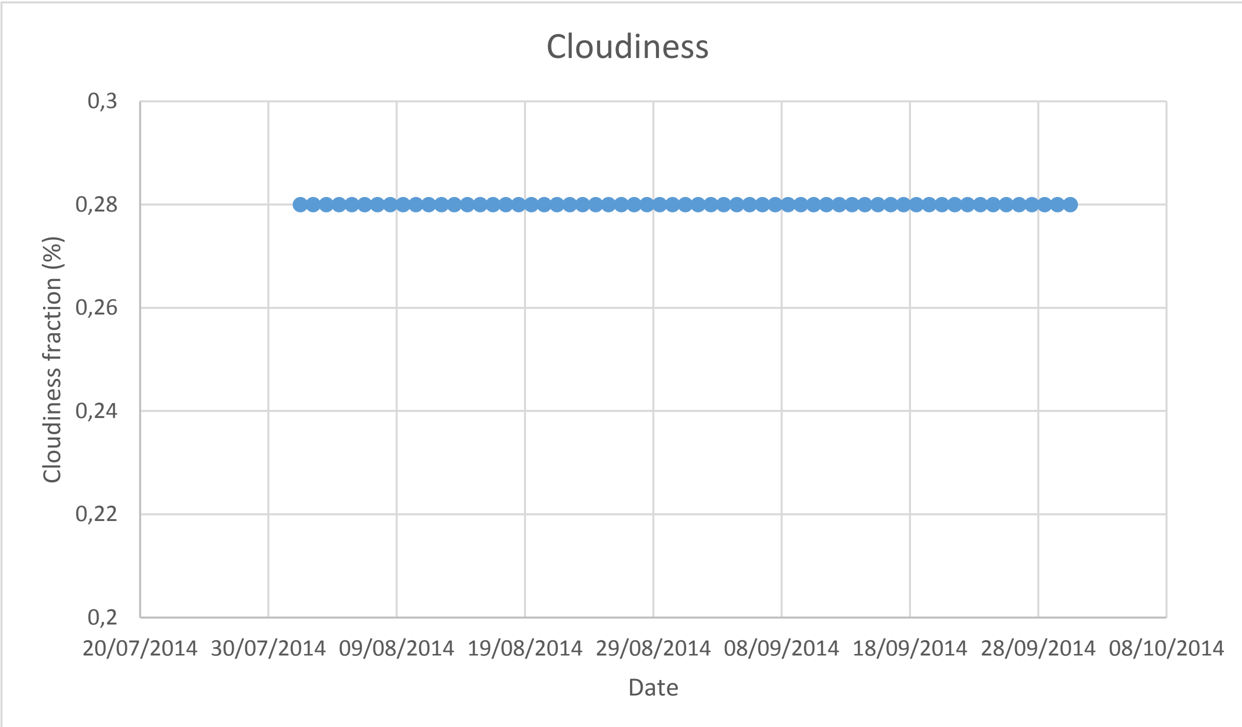
Appendix 1. Input data for the first model

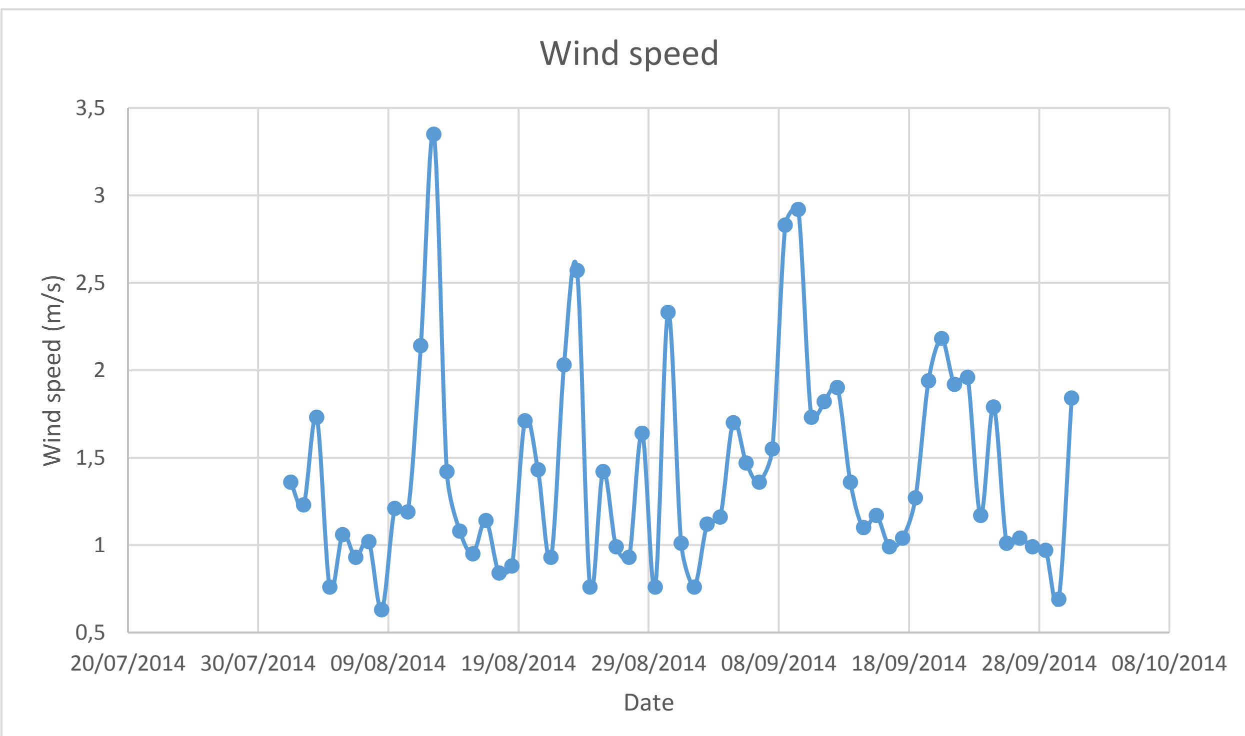




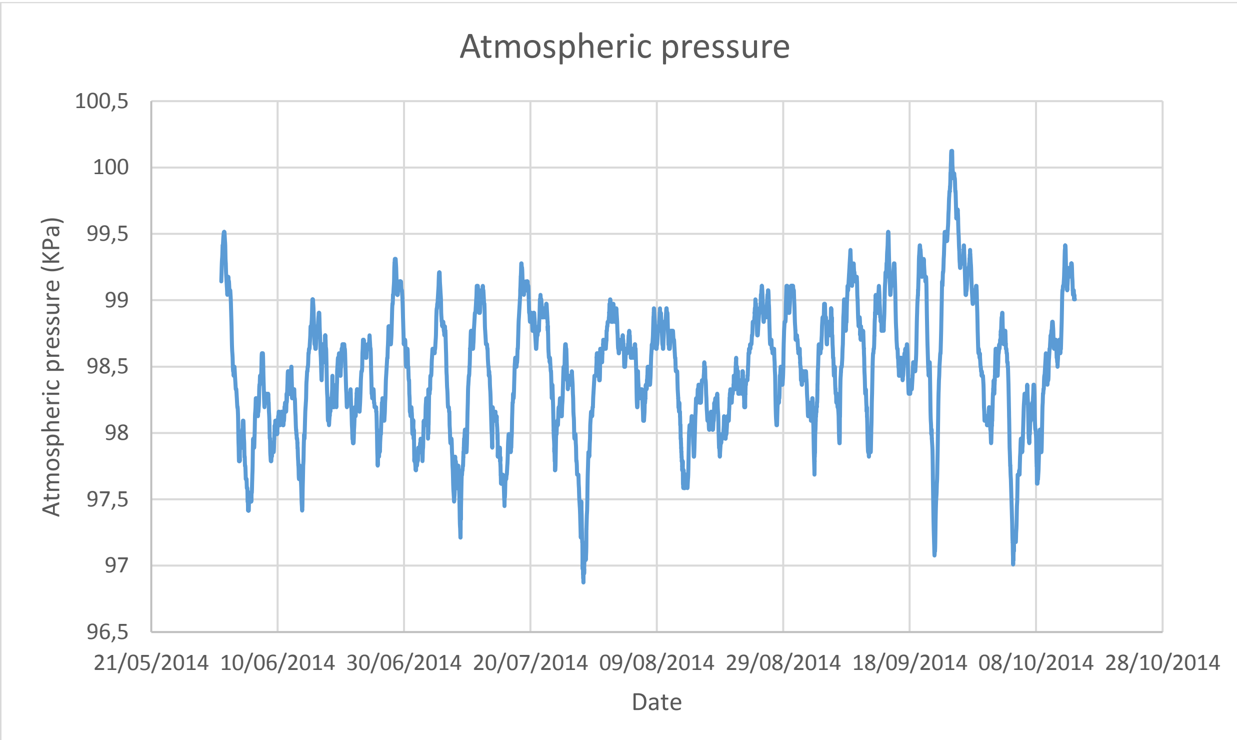

Humidty
110
100
90
80
70
60
50
Relative humidity (%)
20/07/2014
30/07/2014
09/08/2014
19/08/2014
29/08/2014
08/09/2014
18/09/2014
28/09/2014
08/10/2014
Date

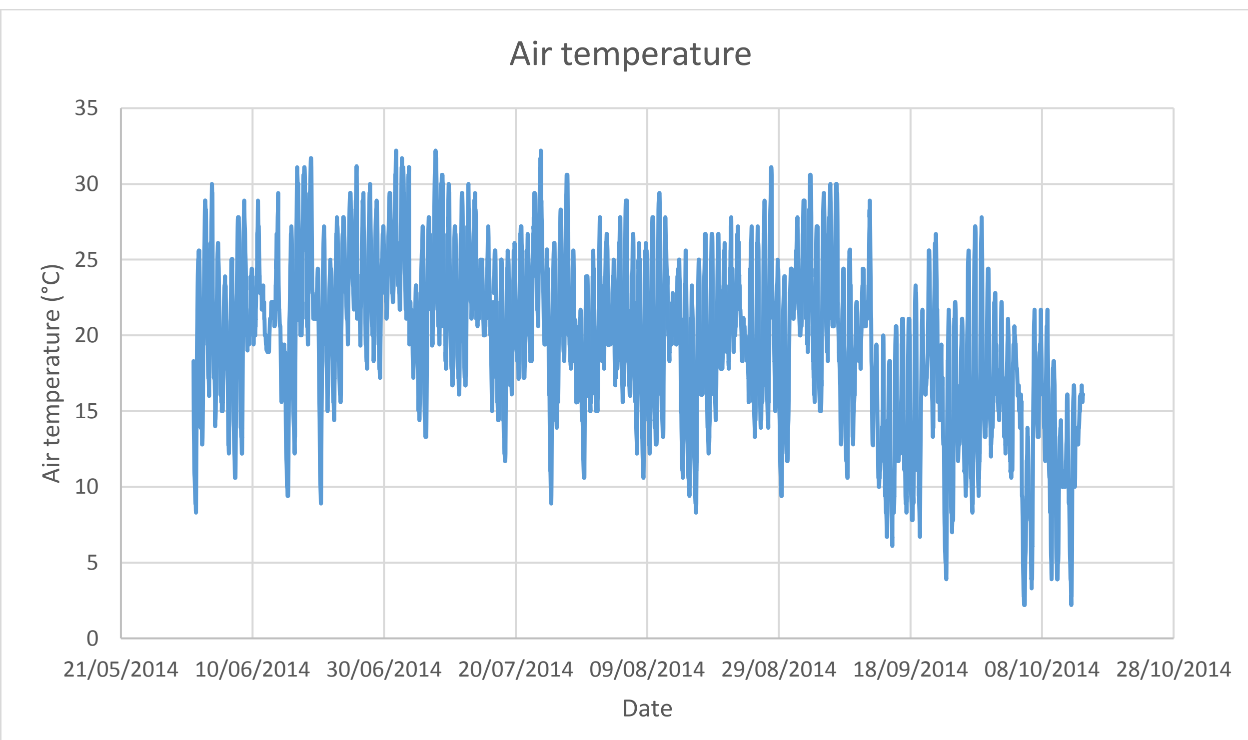

Short wave radiation
700
600
500
400
300
200
100
0
Short wave radiation (MJ/ m² day)
20/07/2014
30/07/2014
09/08/2014
19/08/2014
29/08/2014
08/09/2014
18/09/2014
28/09/2014
08/10/2014
Date

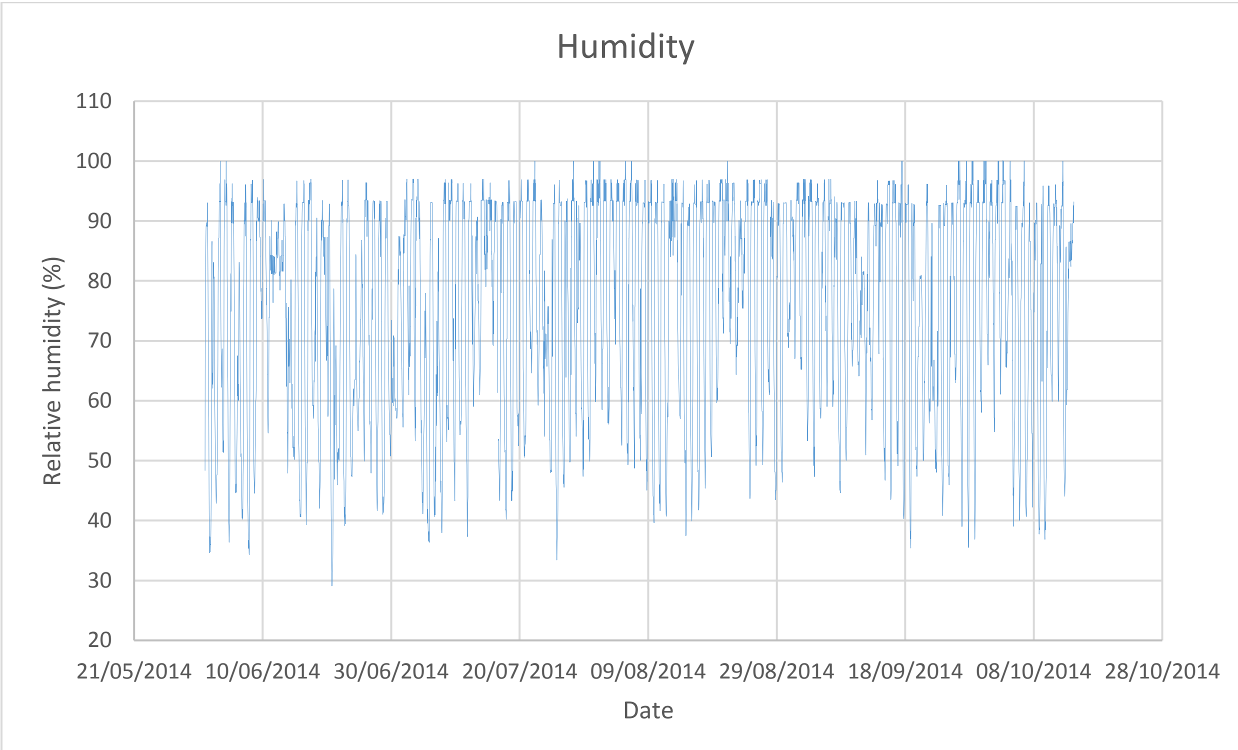

Cloudiness
Cloudiness fraction (%)
0,3
0,28
0,26
0,24
0,22
0,2
20/07/2014
30/07/2014
09/08/2014
19/08/2014
29/08/2014
08/09/2014
18/09/2014
28/09/2014
08/10/2014
Date

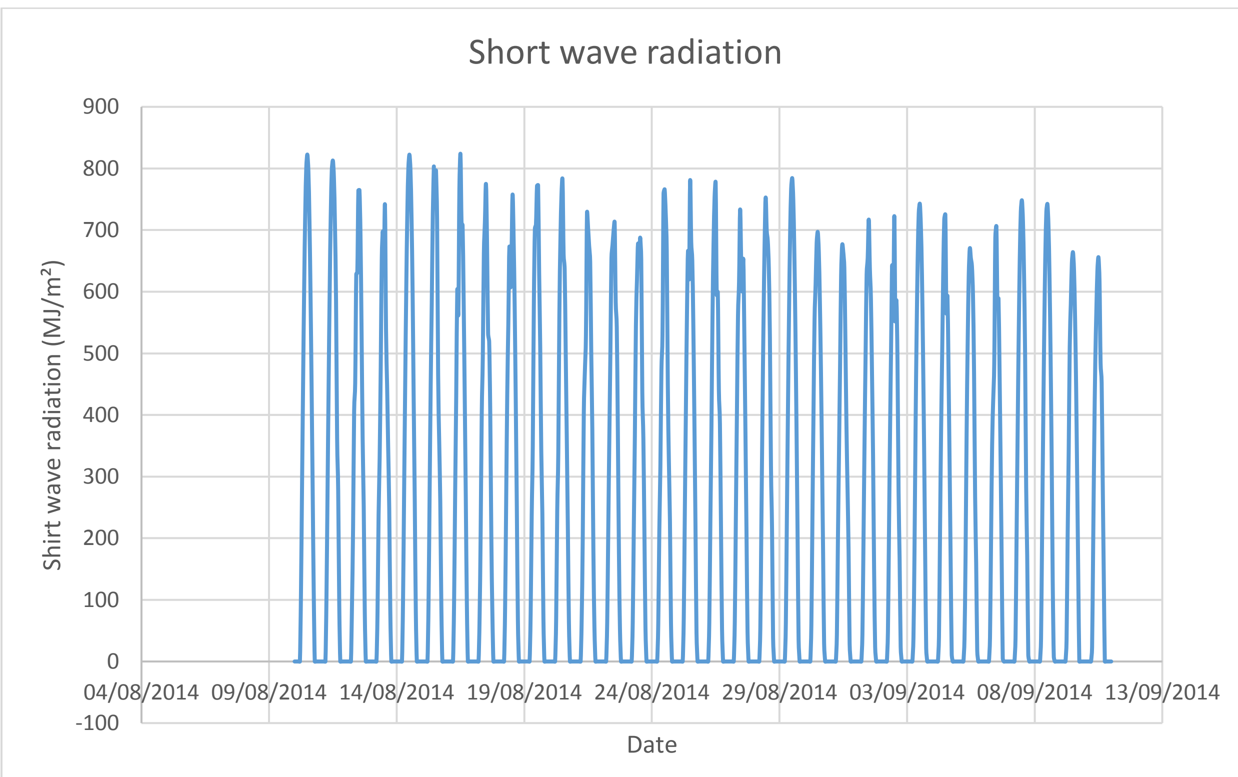

Wind speed
Wind speed (m/s)
3,5
3
2,5
2
1,5
1
0,5
20/07/2014
30/07/2014
09/08/2014
19/08/2014
29/08/2014
08/09/2014
18/09/2014
28/09/2014
08/10/2014
Date

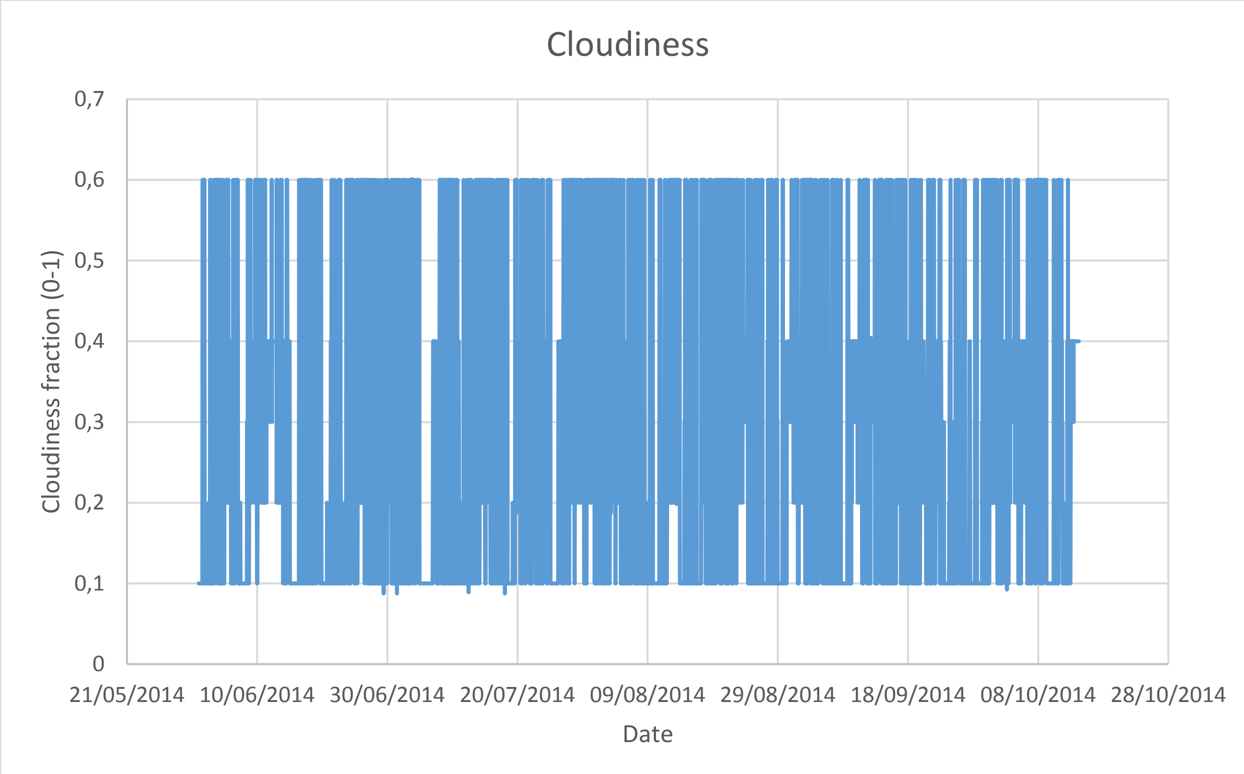
Appendix 2. Input data for the second model

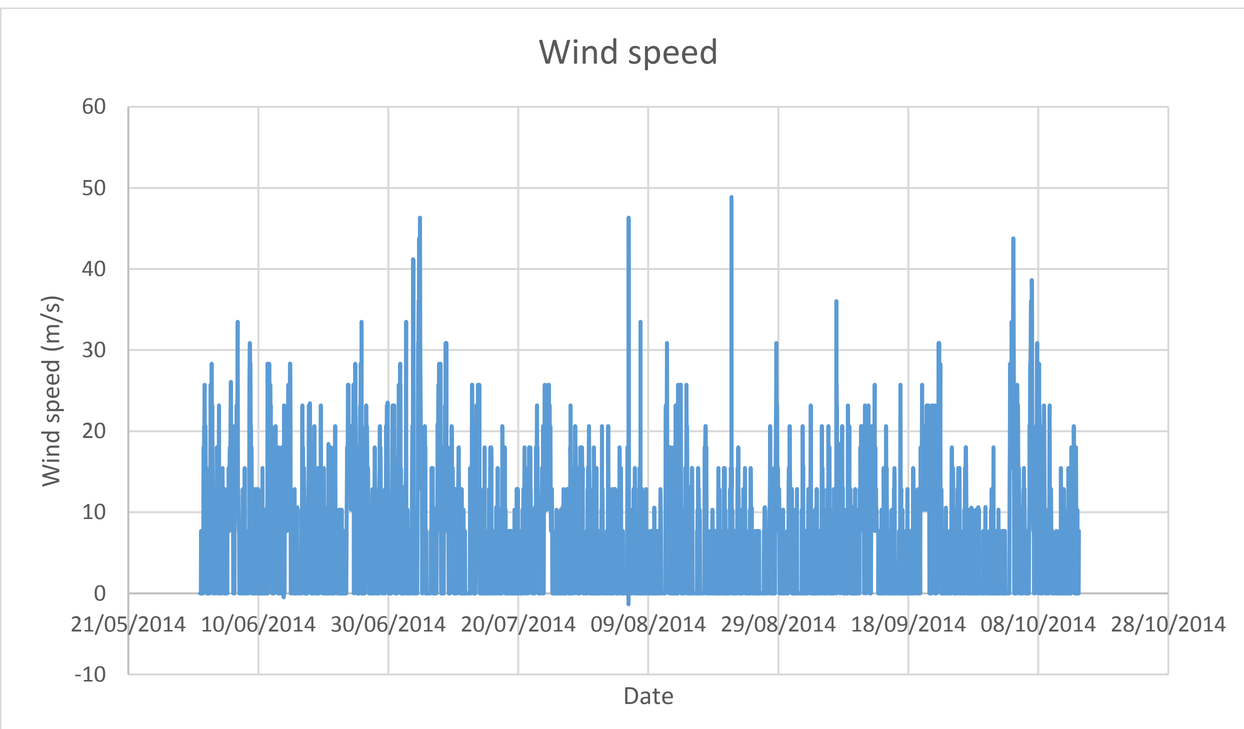





Humidity
110
100
90
80
70
60
50
40
30
20
Relative humidity (%)
21/05/2014
10/06/2014
30/06/2014
20/07/2014
09/08/2014
29/08/2014
18/09/2014
08/10/2014
28/10/2014
Date


Short wave radiation
900
800
700
600
500
400
300
200
100
0
-100
Shirt wave radiation (MJ/m²)
04/08/2014
09/08/2014
14/08/2014
19/08/2014
24/08/2014
29/08/2014
03/09/2014
08/09/2014
13/09/2014
Date


Cloudiness
Cloudiness fraction (0-1)
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
21/05/2014
10/06/2014
30/06/2014
20/07/2014
09/08/2014
29/08/2014
18/09/2014
08/10/2014
28/10/2014
Date


Wind speed
Wind speed (m/s)
60
50
40
30
20
10
0
-10
21/05/2014
10/06/2014
30/06/2014
20/07/2014
09/08/2014
29/08/2014
18/09/2014
08/10/2014
28/10/2014
Date