Development of a GIS-based Model for River Water Temperature Interpolation

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Abstract

River water temperature is an important ecological measure and a complex phenomenon. A significant number of influencing factors with different levels of impact on the water temperature profile, and dynamic water temperature behaviour of rivers, must be considered. Critical factors represent air temperature, shade caused by riparian vegetation, flow velocity and solar radiation. In order to obtain exact water temperature values, on-site measurements have to be performed, however, it is not possible to equip every segment of the river with measuring stations. Therefore, the main goal of this project is the development of a GIS-based water temperature interpolation model that estimates the water temperature in rivers. Essential for this GIS-based model is the detailed definition of influencing factors and its spatial representation for developing an analysis model.

In a first step, the target river network is segmented based on its tributaries. Segment points are set where tributaries join the major river, and therefore cause a mixing due to different water temperatures. Every segment with the calculated values regarding hydrology, geometry, meteorology, as well as shade, serves as an input for the applied water temperature interpolation tool "Stream Segment Temperature Model" (SSTEMP). This tool is used to calculate and interpolate the monthly average water temperature for every river segment. Following this procedure, pinpoint water temperatures are calculated for every river segment that can be exported to ArcGIS. Python Scripts support a semi-automated workflow to transfer all relevant geodata to the corresponding river segment where they are stored as attributes. Finally, the result can be visualized and highlighted, which enables the user to obtain modelled pinpoint water temperature information.

1 Introduction

Rivers are environments combining physical, biological and chemical processes which directly impact water quality. Furthermore, they influence water temperature in rivers, which affects the health and fitness of all aquatic organisms such as fish species (KOYCHEVA & KARNEY 2009). Therefore, sustainable monitoring regarding water temperature should be performed on a regular basis to keep and enhance the water quality within rivers. When measuring temperatures, a maximum accuracy should be approached to know the exact water temperature at any position within the river, however, it would be impossible to equip an entire river with temperature loggers. The dynamics within the

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rivers are caused by influencing factors such as solar radiation, air temperature, or shade caused by riparian vegetation, which make it impossible to graph rivers with linearly rising temperatures from one measuring station to the next one downstream, because the factors influence the water temperature with different levels of intensity. Therefore, a river water temperature interpolation model is required, in order to consider the influencing factors which are present in the defined study area.

The main motivation for this project is the ability to obtain pinpoint water temperature information at any location within the river, without any additional on-site temperature measurements. Simply by modelling information about pre-defined water temperature values, position of the required temperature values, and the intensity and level of impact of influencing factors, the temperature at unknown positions can be modelled. The approach can potentially reduce the amount of in-situ measurements, resulting in a reduction in time, costs, and human resources. The key motivation for the Federal Agency for Water Management – Institute for Water Ecology, Fisheries and Lake Research in Mondsee, Austria, which is a supportive partner for this project, is the ability to estimate river temperatures based on standardized input data, in order to support the river ecology monitoring tasks in the context of the European Water Framework Directive.

In a first step, a comprehensive criteria catalog with the influencing factors on river water temperature was defined. Together with an evaluation of existing river water temperature models, this criteria catalogue provides the conceptual framework for the model. One problem which arises is the definition of an appropriate and universally valid model and workflow. This is problematic as no universal model exists, which fits perfectly to any study area. Therefore, the model has to be customized according to the study area of this project (BOGAN et al. 2003). The main and final result is the implementation of a GIS-based water temperature interpolation model, and a semi-automated workflow is processed in ArcGIS using Python Scripts. The potential influencing factors are derived from standardized geodata sources, and processed and transferred to the target river. For each river segment a mean water temperature is calculated and can be visualized in a GIS.

2 State of the Art and Literature Review

2.1 Water Temperature in Rivers

In general, rivers provide habitats and spawning grounds for fish species and microorganisms. Because they are used to constantly prevailing water temperatures, they are sensitive regarding water temperature changes which are caused by global warming. Fish species are indeed used to the variability of temperatures over the whole year, caused by seasonal variability, but they are not able to adapt to increasing temperatures caused by global warming. One effect which may occur is that they change their habitat and spawning grounds upstream to habitats with a higher elevation and colder water temperatures (PRINZ et al. 2009). Due to the sensitive behaviour and lacking flexibility of fish and microorganisms regarding changing circumstances within the river, the consequences of rising water temperatures on the fish fauna and the ecosystem of rivers is going to be crucial, as they only have a specific temperature range which they are able to tolerate (CAISSIE 2006).

Another aspect which plays a role concerning river water temperature is the term of variability that is mainly caused by influencing environmental-factors. Due to the fact that river water underlies a natural heating process, the factors which influence the temperatures such as inflows, shaded areas or karstic springs occur inconstantly. The variability of the temperature is defined by the factor itself, the level of intensity and the type that defines the factor to occur on a global, local or regional basis. This variability makes it difficult to give exact temperature estimations within the river because the variability is unknown. To obtain information on all the variables of water temperatures within rivers, the influencing factors have to first be determined, and subsequently analysed to receive information concerning interactions and relations with other factors.

2.2 Influencing Factors on Water Temperature

Influencing factors on water temperature are elements which either increase or decrease the temperature in rivers. In general, they can be divided into the four major groups, namely, *riparian vegetation* (height, type, and density), which causes shade to the river, *channel engineering* (groundwater flow and riverbed), which comprises the facts regarding the situation inside the river, and *thermal pollution* (industrial use and hydrological changes), which defines the influences from the outside to the river. Additionally, *weather conditions* (air temperature, solar radiation, cloud cover and wind speed) directly influence riparian vegetation (KOYCHEVA & KARNEY 2009). This classification model is visualized in figure 1.

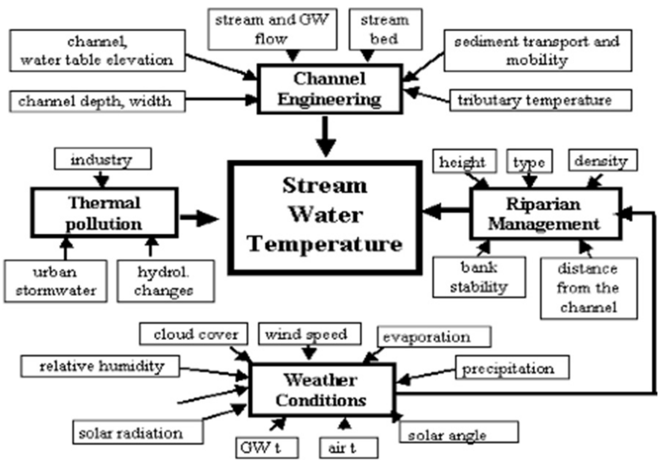

Fig. 1: Factors affecting water temperature (KOYCHEVA & KARNEY 2009)

3 Approach/Concept

Influencing factors on river water temperature are categorized based on a customized classification scheme. In a next step a conceptual analysis model is designed, and existing water temperature models are compared and evaluated. A special issue in this context is the definition of a geometrical segmentation scheme of the river network.

3.1 Influencing Factors on Water Temperature

Compared to the classification model in figure 1, a customized categorization was developed for this project. Besides factors already defined in figure 1, new factors are added, which are not considered in this classification model. Karstic- or hot/thermal springs are just two factors which have to be considered as they are present within the study area for this project. The categories of influencing factors for this project comprise the following:

- Climate and Weather Conditions (e.g. air temperature, solar radiation)
- Shading (e.g. shaded area, wind sheltering)
- Industrial River Water Utilization (e.g. power plants cooling, sewage plants recharge)
- Catchment Area (e.g. elevation, tributaries)
- Hydro-Geological Setting (e.g. type of substrate, karstic springs)
- River Characteristics and Morphology (e.g. slope of river segment, average depth)
- River Hydraulics (flow velocity, flow regime/turbulences)
- Human Constructions (e.g. barrages, reservoirs)

In total, 53 factors have been identified based on a literature survey, as well as defined by experts of the Institute for Water Ecology, Fisheries and Lake Research. The key influencing factors are defined to be air temperature, solar radiation, shading caused by topography and riparian vegetation, as well as tributaries (MOHSENI & STEFAN 1999; JOHNSON 2004; BOGAN et al. 2006).

3.2 Water Temperature Models

For this project, eight river water temperature models were validated and ranked based on the criteria catalog:

- ATV-Gewässergütemodell
- BasinTEMP – Stream Temperature Model
- CE-QUAL-W2 – Hydrodynamic and Water Quality Model
- HeatSource – Stream Thermodynamics and Hydrology Model
- QUAL2K – River and Stream Water Quality Model
- SNTEMP (Stream Network Temperature Model)
- SSTEMP (Stream Segment Temperature Model)
- SWAT (Soil and Water Assessment Tool)

According to the rank, the so called Stream Segment Temperature Model (SSTEMP) has been identified to be the most suitable tool for the purpose of this project (BARTHOLOW 2004). SSTEMP is a model for calculating river water temperatures by considering various influencing factors on water temperature. The software differentiates between input types such as hydrology, meteorology and geometry, as well as river shade, which can be seen in figure 2.

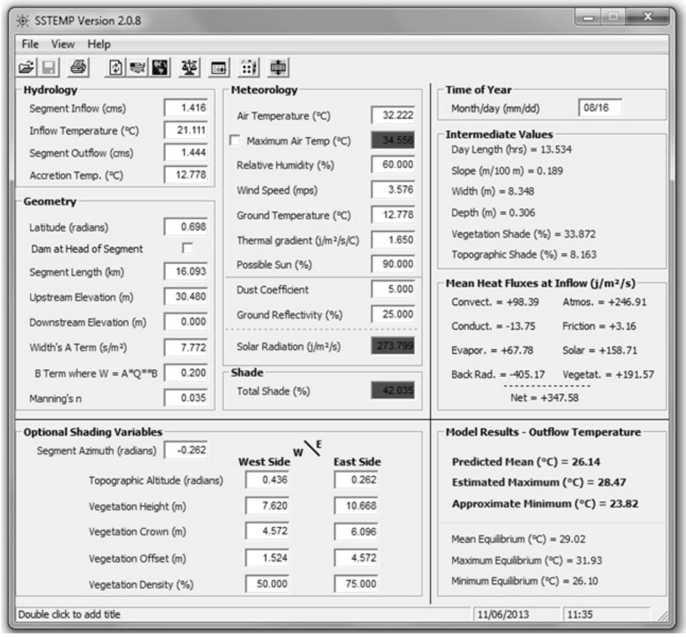

Fig. 2: SSTEMP – User Interface

After defining input parameters, SSTEMP predicts the mean daily water temperatures for a specified distance downstream. After setting the parameters, SSTEMP provides the option to perform sensitivity- and uncertainty analysis based on the input values. The final temperature values are stored within an external file, which can be exported as well as imported (BARTHOLOW 2004).

3.3 Segmentation Scheme

Due to the fact that SSTEMP requires river water segments as input data, the major river has to be segmented before interpolating values on the segments and importing the data to SSTEMP. The segment points are set where the river temperature is influenced by tributaries. Every time the temperature of the river is mixed due to temperatures caused by tributaries, a segment point is set. The inflow water temperature for the following segment is calculated according to the mixture's temperature equation by Richmann, using the outflow temperature and discharge from the previous segment and the temperature and discharge from the tributary (CZICHOS & HENNECKE 2004).

4 Workflow

Figure 3 provides an overview of the analysis workflow and the integration and coupling by automated scripts of the SSTEMP model with a GI-System. The GIS acts as a tool for pre-processing the necessary model input data, and also for visualization of the model results. In this prototype, the parameterization and data exchange between the GIS and the SSTEMP model is implemented by simple text file exchange.

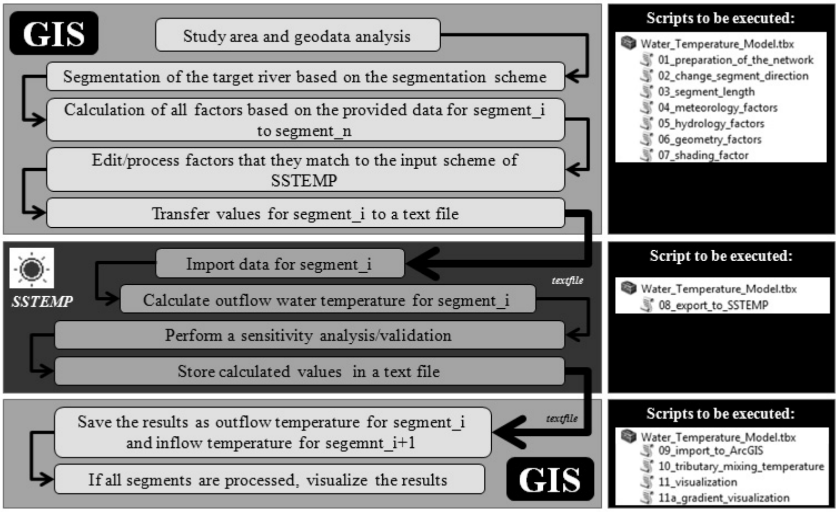

Fig. 3: Workflow of the project

4.1 Study Area and Geodata

For this project, a study area at the river Gail in the Gailtal in Carinthia (Austria) was selected. The length of this river test site from Kötschach-Mauthen to Nötsch is 56 kilometers. Within this study area, 16 tributaries flow into the river Gail, and, therefore, the study area is divided up in 17 single river segments which serve as sequential input segments for SSTEMP. After the study area is defined, relevant geodata have to be acquired. All data sources are required, which are defined as parameters in SSTEMP. Data providers are the CENTRAL INSTITUTE FOR METEOROLOGY AND GEODYNAMICS (ZAMG), the Carinthia Geographic Information System KAGIS, the Department of Hydrology of the Carinthian Land Government, as well as the Department of Ecology and Monitoring of the Carinthian Land Government. Most of the geodata have to be transformed until they match to the input requirements of SSTEMP.

4.2 River Network Preparation

Before interpolating values from the geodata sources to the river segments and segment points, the river network has to be prepared. The first step after the segmentation of the river according to the segmentation structure is to execute script *01_preparation_of_the_network*. This script adds all necessary fields and parameters which are mandatory for the data export to SSTEMP. After adding the fields to the shapefiles, the major river is split based on the set segment points. Because the internal algorithm of ArcGIS which splits the segments sets arbitrary IDs, the segments have to be re-ordered. The final order should match the flow direction of the river. This is performed by executing script *02_change_segment_direction*. After the segments are in the correct order, script *03_segment_length* is the next script to be executed. The algorithm iterates through each segment and stores the length. All scripts which were executed so far are not required to be executed again.

4.3 Transfer Values to River Segments

After the river has been split to river segments and re-ordered, further scripts can be executed which calculate values for each parameter based on the geodata sources. Script *04_meteorology_factors* is the first script to be executed which calculates the meteorological factors for the target segment. This script calculates temperature values for the target segment. To guarantee an interpolation to the segment, the values first have to be calculated for the segment points. The value for the segment point is calculated by interpolating temperatures based on the data provided by the ZAMG. The interpolation takes place based on the elevation, which is decisive for the air temperature of the segment point. The values for all meteorology factors are calculated in a similar manner compared to the air temperature, by interpolating values from the segment points.

The next script *05_hydrology_factors* calculates the inflow- and outflow values for the segment by calculating the discharge for each segment point. They are calculated by applying the GMS-formula by Gauckler, Manning and Strickler (JIRKA & LANG 2009) for the tributaries, as well as provided by the Department of Hydrography, followed by an interpolation. The next script *06_geometry_factors* calculates the discharge for each river segment and transforms the values to customized width's A- and width's B terms which are required by SSTEMP. The following script *07_shade_factor* estimates the area covered by shade for the whole river segment.

4.4 Data Export and Import

After calculating each factor for the major river water segment, the segment data can be exported to SSTEMP with the goal to calculate the mean monthly river water outflow temperature for the target segment. This segment serves as the inflow temperature for the following segment as well. To import the values to SSTEMP, the software requires an input text file with a pre-defined formatting style. By executing script *08_export_to_SSTEMP,* the pre-calculated attribute information from the target segment is transferred to a text file under the consideration of the required formatting style to enable the import to SSTEMP. If the text file is opened in SSTEMP, the parameters automatically change from default to the calculated values from ArcGIS. Without pressing any buttons the mean monthly water temperature is calculated on the fly and visualized besides estimated mean- and maximum temperatures. After a sensitivity analysis which can directly be performed in SSTEMP, the result values can be exported to a text file that can be re-imported to ArcGIS.

To re-import the calculated monthly mean water outflow temperature for the target segment, the script named *09_import_to_ArcGIS* which reads the temperature value from the output text file needs to be executed. The only value which is parsed from the text file is the predicted mean water temperature compared to all other information such as segment inflow, air temperature or possible sun which is ignored. The outflow water temperature value for the target segment automatically overwrites the value for the outflow temperature in the attributes of the target segment. Besides, this value is also stored as inflow temperature for the following segment. If tributaries are entering the major river at the outflow of the target segment, which is the case at every segment point, the outflow temperature no longer equals the inflow temperature of the adjacent segment. Therefore, the inflow water temperature has to be re-calculated and overwritten. Before the values of the target segment are exported to the text file which will be imported in SSTEMP, the script named *10_tributary_mixing_temperature* has to be executed. To calculate the mixture's temperature between the target river segment and tributary, the discharge and the temperature of the tributary are mandatory parameters. The inflow temperature for the target segment, which is equal to the outflow temperature of the previous segment until now, is updated according to the discharge as well as the temperature of the tributary.

5 Results

Monthly mean river water temperatures for each segment are calculated and stored as attributes of each segment. The results can be visualized by executing script *11_visualization*. Based on a predefined color scheme, the user can immediately see the temperature values for each segment within the major river. The only disadvantage regarding script 11_visualization is that a segment which is longer than 5 kilometers is visualized using one single color value for the entire segment. In order to provide a visually more appropriate visualisation, script *11a_gradient_visualization* splits each segment to sub-segments providing a more smooth gradient visualization. Figure 4 depicts the results of a water temperature calculation for August 2012.

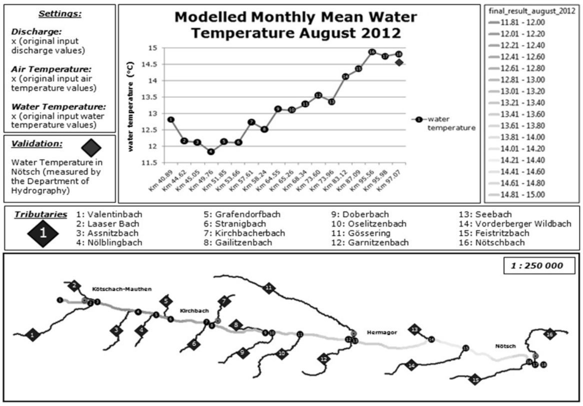

Fig. 4:
Water temperature estimation for August 2012

For the river water temperature estimation for August 2012, it is demonstrated that the river underlies an expected general continuous warming process in downstream direction. Exceptions are at present caused by tributaries mixing temperatures with the major river, which are colder than the temperature of the river Gail. At the end of the study area the water temperature is estimated to be 14.83 °C. If the temperature development calculated by the model is compared to measured values by the Department of Hydrography of the Carinthian Land Government, the estimated water temperature for the outflow would be just 0.3 °C higher compared to real values where the measured temperature is 14.53 °C.

By manipulation the input values for the model, scenarios regarding flood, drought or global warming can be performed. Within this project scenarios have been developed for flood with doubled discharge values for the river and the tributaries, drought with halved discharge values and a simulation of global warming up to 2050 by increasing air temperature values. Because there is a correlation between air- and water temperature

(MOHSENI & STEFAN 1999), increased air temperatures also assume increased water temperatures for the future. The results show that an increased discharge results in colder temperatures over the entire study area. This is caused by the heating process by the solar radiation which is decelerated by increased water volumes because it takes longer time to heat up the water. Compared to the flood-scenario, the temperatures increase faster when the discharge of all tributaries is halved. Because the tributaries in general have lower water temperatures compared to the major river Gail, the tributaries have a cooling effect on the river temperatures. Due to halving the discharges, the cooling effect is mitigated. Figure 5 shows the temperature development considering all scenarios.

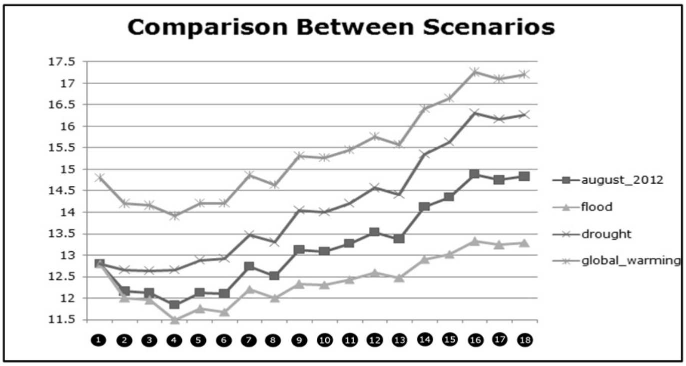

Fig. 5: Comparison between scenarios

6 Conclusion

To conclude, the goal to develop a GIS-based water temperature interpolation model including a semi-automated workflow within ArcGIS was reached. It was analysed which factors influence water temperatures in rivers. According to meetings with experts, the decisive factors which are the dominant contributors to river water temperature were defined. Furthermore, it was shown that water temperature interpolation in rivers is possible and how it can be realized. Under the usage of an already existing, well-engineered and validated water temperature model named Stream Segment Temperature Model (SSTEMP) the geodata, which have to be transferred to river water segments, can be imported via an interface that enables the import/export of text files with predefined format. Before transferring segments to SSTEMP, they have to be created by performing segmentation and re-ordering based on the major river which is the river Gail in Carinthia. Using Python, the scripting language within ArcGIS, the semi-automated workflow was created which transfers data from the raw geodata to the target segment and stores them as attributes which can further be exported to SSTEMP. Due to scripts, which can be executed sequentially step by step, the workflow automatically transfers the geodata by applying algorithms programmed using Python, except for three settings which have to be performed manually by the user.

The main conclusion which can be drawn out of the realization of this project is that the distinct determination of the pinpoint river water temperature information is aggravated by the dynamic temperature behaviour and situation within rivers. This makes impossible to define the precise pinpoint temperature without any in-situ measurements. Circumstances such as the constantly changing riverbed, flow velocity differences, as well as flow regime within the river make it difficult to give exact statements regarding the precise water temperature at one specific point within the river. Therefore, the river water temperature interpolation, as well as –estimation, which were performed in this project provide an approach to the precise and accurate pinpoint water temperature information.

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