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RESEARCH ARTICLE

Space-Time Ice Monitoring of the Hungarian Lower-Danube

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Abstract

In spite of global warming, an unusual combination of hydro-meteorological conditions can still produce serious frosts, and consequently ice floods on the Hungarian reach of the Danube river. Therefore a monitoring system was developed during the last 15 years in the region for a 130 km segment of the Danube. All together five cameras were installed at a 30–40 km interval to achieve optimal observational capabilities along the river. In January 2009 and later in February 2012 two ice events were successfully recorded at the monitoring locations. Primary analysis of the recorded events combined with ice depth measurements, morphological information and hydro-meteorological data showed great potential to derive space-time characteristics of the floating ice. These include ice formation, size composition, motion and rearrangement due to secondary currents and occasional packing or release at places. Repeated measurements have been done to quantify the space-time characteristics of the ice formation and to improve the , monitoring system. There have been several chances for utilization our gained experiences such as characterization of drifting floes, study of the hydrodynamic conditions during icy periods, verification of floe modelling, discharge estimation using LSPIV technique and additionally development of ice fore-casting. Last but not least a new ice thickness staff was intro-duced for the easy and safe measurements of ice floes on rivers.

Keywords

ice flow, floe, web-camera, ice depth, monitoring

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1 Introduction

Research using up-to-date technology in the field of river ice has been intensified on the southern Hungarian reach of the Danube. In the past, the most severe floods on this part of the river were caused by ice jam [1]. During last 180 years serious ice floods occurred on the Hungarian Danube in 1838, 1839, 1850, 1876, 1878, 1883, 1891, 1920, 1923, 1926, 1929, 1940, 1941 and the highest ever experienced in 1956. The two main reasons for ice flood are hydro-meteorological conditions, and morpho-logical factors. In the southern region river restoration, the most important morphological factor was completed long time ago and it constanty works against ice formation. Since then only mainte-nance and small corrections were done occasionally [2].

At first the frequency distribution of ice occurrence during the last 115 winters was developed (Fig. 1) From that, it can be observed that the ice occurrence was much lower in the last 45 years than in the 70 years before. The days with the highest probability that ice could be seen in the investigated area were 5–10 days earlier in the last decades: between January 14–19 there was a 22 % chance to see ice on the Danube between 1971–2015, while the peak value was 61 % and between 19–25 January in the period 1901–1970.

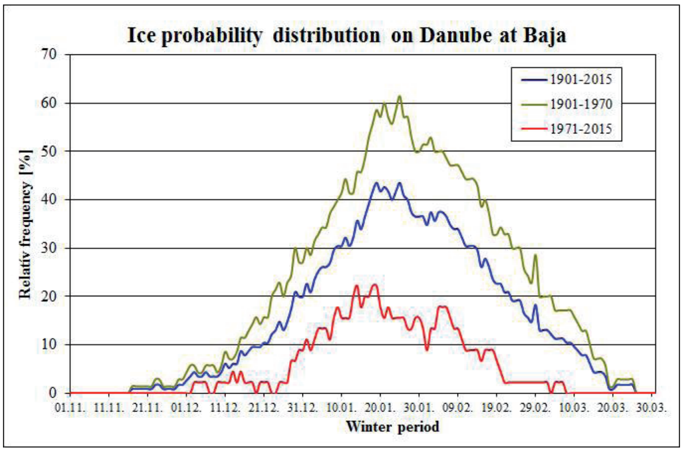

Fig. 1 Probability of observed ice phenomena on the Danube at Baja for the days between Nov 1 to March 30 averaged for years 1901-1970, 1971-2015 and 1901-2015.

In spite of global warming, which is clear from observations of the past couple of decades, an unfortunate constellation of hydro-meteorological factors can cause serious frosts, and consequently, ice floods anytime.

Prevention of floods and managing flood damage is a main task of the Hungarian Water Management Service. To achieve this goal reliable hydrological observations are extremely important [3]. However fluvial ice monitoring is a rather neglected field of hydrology in Hungary. Only the percentage of ice cover is estimated by eyesight during frozen periods. This is inadequate for detailed investigations about the whole freezing, floating and jamming processes that require objective and reliable data.

As an initial step towards this goal, in 2001, a web-camera was installed (Fig. 2) on top of a high building at the riverbank in Baja. The web-camera was developed using earlier experiences with conventional black and white photography. In 2008 based on the success of the first measurements a monitoring program was developed, by installing 5 additional cameras.

Fig. 2 First web-camera installed on top of a silo at the bank of Danube

The monitoring sites were placed at a 30–40 km interval along a 130 km reach. In the first winter after installation (January 2009), a two-week-long ice period was successfully recorded at the five locations. Since then, only in February 2010 and 2012 was ice observed on this reach of Danube. In 2012 the ice flow of Danube was taken seriously by the river managers and even the ice breaker fleet was activated. During that time the ice breaker ships were used for ice thickness measurement as well. To achieve quick and reliable measurements a new and easy equipment was introduced called "Keve-staff" [4].

A primary analysis showed that when these measurements are combined with morphological information and meteorological data, space-time characteristics of the floating ice can be potentially derived. These characteristics include size composition, motion and rearrangement due to secondary currents and occasional packing or release at places. Efforts are being done to quantify the above mentioned features, furthermore, improving the recording quality thus the image processing results of the observations.

The article introduces the short history of Hungarian fluvial ice monitoring and its developments in the last decades. Then it highlights the importance of the new webcamera observation system. Taking under consideration the hydro-meteorological conditions that influence local ice formation and the experiences with webcams, we demonstrate the use of the collected data to determine ice floe dynamics, provide parameters for modelling, estimate discharge, and forecast the appearance of ice cover. The author also tackles the problem of ice thickness measurement and offers a new staff that easily acomplishes this job. Lastly, conclusions and some recommendations are also given for future developments and investigations.

2 A camera-based fluvial ice measurement system

2.1 Background

In 1978 Zsuffa [5] wrote a technical study about appropriate methods of ice measurements on rivers. He states that there are quantitative and qualitative tasks for proper ice observation.

The first qualitative task is watching the ice, which is done by an ice guard person. This is a very common method all over the world, but rather subjective. The observation is coded and recorded in hydrological databases. The data can be used later for further investigations, but the information is commonly limited to the surroundings of river gauging stations. The codes tell us about the appearance of ice, ice drift, stopping of ice floes, breaking up, ice jams and the disappearance of ice. During this observation the percentage of ice cover zones to the total water surface area of the surveyed river section is also recorded, but it highly depends on the viewpoint and estimation ability of the observer. For this reason, there is a need for a more reliable qualitative observational measurement of the ice. To solve this problem an observational technique using analogue photographic cameras has been invented by Zsuffa (5). The observed quantities include the percentage of ice cover to the total water surface area of the section, the percentage of drift floe to the standing ones, the velocity of drifting floes, the ice surface discharge [m^2/s], the thickness of ice, and as a main result the ice discharge [m^3/s] [5, 6]. This technique, combined with ice thickness measurements, is not widely spread yet. in Hungary.

Zsuffa's method was further developed by replacing analogue cameras with digital webcameras. The main task with cameras is to orthorectify the perspective image of the camera which is highly dependent on the location, and orientation of the observation point. The best location is vertically above the observed section of the river and the orientation is perpendicular to the river. Using this type of placement the perspective error could be minimised. Satellite images or aerial photos are alternatives to webcameras, but they are still too expensive for the required resolution and the necessary picture capturing frequency.

The rule of thumb is that the observation height should be at least 5-10 % of the total width of river and it needs to be as close to the river as possible. The best installation is when the camera objective lens can see both river banks and the vision is at a right angle to the stream [6]. At this elevation some of the errors of low perspective can be minimised as well (Fig. 3).

Fig. 3 Different views at the same time and section of Danube at Baja town (10:00 am 01/07/2002)

There are several limitations to install webcameras on the river bank. The two most important are the electric supply and the network connection to transmit computer signal. To avoid interruption in operation, a continuous power supply (UPS) and an autonomous electric connection are recommended. During our monitoring program the electricity was turned off once in the hosting building because of a serious flood. It is important to think about these problems during the planning period and take preventative measures. [2]

On a lowland river reaches it is often hard to find a natural or artificial high place on the banks where all the listed placement conditions can be fulfilled. Grain towers, high buildings or large bridges along the river are the best locations. Natural hills or cliffs are good locations to place the webcameras, but the electric supply is hard to find if there are no houses nearby [7]. Locations that are already difficult to reach in summer can hardly have an access in a frozen winter. Even after finding a good placement, any kind of structure (antenna) can still block part of the camera view. A wireless connection can be used to transmit data but sufficient and continuous electric supply is still crucial for this application. Heating is necessary for outdoor cameras during winter. New cameras are more powerful, since they can signal, zoom or move but these options may also come with a high use of power. Reflection of the sun or the water during most of the day also makes data interpretation difficult. With all of these considerations, custom-designed placing of cameras is recommended. [7]

Finally, it is important to mention maintenance. The objective lenses of these outdoor webcameras can become dirty (due to bugs, dust, snow, sleet, etc.), thus the lens require regular cleaning. A number of problems can be experienced during the operations of cameras. An insufficiently closed outdoor cover can offer hiding place for insects, which is hard to clean then. Pigeons, falcons can sit on the camera (leading to shaking) if there is no higher place in the surroundings. Electrical short circuiting can also make operating troublesome. But the most significant problem that prevents efficiently using the cameras is usually the occasional high limitation of the daytime visibility by the actual weather. During the night and in foggy situations or bad reflection conditions we have practically no information about the monitored river reach. According to our knowledge infrared cameras have not been developed for this particular purpose, or if they have a camera handling more than 500 m distance must be rather expensive.

There are many webcams available in the market, but for quantitative basic monitoring even a simple fixed camera is sufficient, serving as a reference site. It is like the datum of a water level gauge, as for the rest of time this camera will continuously provide pictures exactly from the same viewpoint. For more complex monitoring advanced technology cameras can be used. In one application such a camera was installed in the middle of a steel bridge structure facing upstream [4]. Here the main stream is placed at the right bank which is on the left side in the camera's picture. But the ice drift occurred on the left and on the right side alternatingly. The turning and zooming facility made it possible to follow this alternation of the ice behaviour. Naturally, some of the measurement information had to be dropped in favor of tracking the changes in the ice movement.

The resolution of digital cameras becomes better and better, but as a consequence we need larger and larger bandwidth to transfer the pictures. Transferring the pictures on FTP (file transfer protocol) can be done online to several addresses at the same time. In fact, these are the main reasons underlining the use of webserver-cams. In this case there is no need for an extra PC to control the camera, instead, everything can be commanded from a comfortable remote place. Hopefully the progress in file and image compressing techniques will solve many of these problems. Furthermore, smart phones can be soon applied for taking adequate pictures and making use of their fast, multiple and cheap forwarding capability.

There is no doubt drones (Unmanned Aerial Vehicles) will be soon used for different areas of hydrometry and thus in ice observation as well. But till that time comes, we have to rely on using land-based cameras.

2.2 Online river monitoring

Since 2001 many events unrelated to ice have been recorded on the investigated reach of Danube that are important for river management purposes. For example, a ship crashing a bridge pier and a deadly canoeing tour accident were recorded [7]. Based on our images the police could have a real picture about the accidents [7]. Some oil spill was also detected and the ship was identified which released its waste oil during the night. High-speed replay of water leves changes could provide novel information on significant flow regime variations as well. Water quality experts tried to find a correlation between the color of water and its biochemical parameters [4]. Water management and navigation authorities, water police, the emergency service and the meteorological service (cloud and weather image) were the main users of the system. Additionally, people even from remote places frequently visited our former web site and observed the river.

After the first installation,in 2001 ice events seldom occurred and only for a short time. These records were sent to researchers at the University of Iowa for processing. The Particle Image Velocimetry (PIV) method was used [8] to generate velocity vector fields based on subsequent images. Unfortunately, without knowing the exact position of the camera and some well identified reference points, further calculations could not be done (Fig. 4) at that time. Ettema [9] and Jasek [8] investigated the relationship between surface velocity distribution determined by ice webcams, PIV and the average velocity of the total cross-section. This method is an important technique to determine discharge in the river and there is hardly a more reliable method in icy conditions.

Fig. 4 PIV-reconstructed surface velocity vector field by Marian Muste, U. of Iowa

Kimura et al [10] developed a method using current meters, remote water level gaging, wind sensors and web-cam to measure factors determining the velocity field in such a way that estimating the discharge in a known cross-section became possible. However it is not easy to find a reliable relationship between the surface velocity distribution and the cross-sectional average velocity. This method needs more detailed investigations. Moreover, floes can clash to each other, which disturbs the path and speed of the individual elements. It is known that the velocity of such inertial floating bodies does not entirely match the one of the water. Sokoray-Varga and Józsa [11] used Particle Tracking Velocimetry (PTV) method in laboratory conditions to reconstruct the flow field of the water surface. According to their experiments there is always some slip of the tracers compared to the underlying flow field that results in some error in the water velocity estimation. On the other hand there can be problems with camera captures as well. Another important factor is the distribution of floe drifts. When the floe drift is not significant, often only part of the section carries ice (usually in the main stream). Since the camera focuses only on the ice, there will be no velocity information about the rest of the section. Several years of experience shows that evenly distributed floe drifts seldom occur in the investigated section of the Danube. But it makes a sence only at river discharge calculation

Another consideration is that the drift is a continuous space-time varying process, even in steady-state water flow conditions. This is why Zsuffa [5] classified this phenomenon as an inherently stochastic process where the description and quantification can be done preferably by proper statistical parameters drawn from the measurements. The outcome of web-cam based monitoring system is suitable for such a purpose. However, software for such data processing and offering a complete statistical evaluation is not known presently by the author.

Gálai [12] investigated the distortion caused by such cameras in operation. In his work the perspective distortion and the camera's self-distortion were both analyzed. With simple linear algebraic methods all the distortions could be eliminated. He also tried to develop methods for automatic ice cover recognition too, but his research stopped in 2010.

Documented historical water level observations can be utilized by modern time processing technologies. This can be the case for webcam based ice monitoring as well, when the primary task is to well document and archive prevailing phenomena.

2.3 Multiple webcameras on the Danube reach

The first experience with our single webcam and the increasing number of questions made it evident that the real-time ice observation can be extended from one single section to a longer river reach. After seven years operation of the first webcam an EU INTERREG III/A project provided good opportunity to develop a monitoring program with five more web-cams, covering a 130 km long reach along the Danube (Fig. 5).

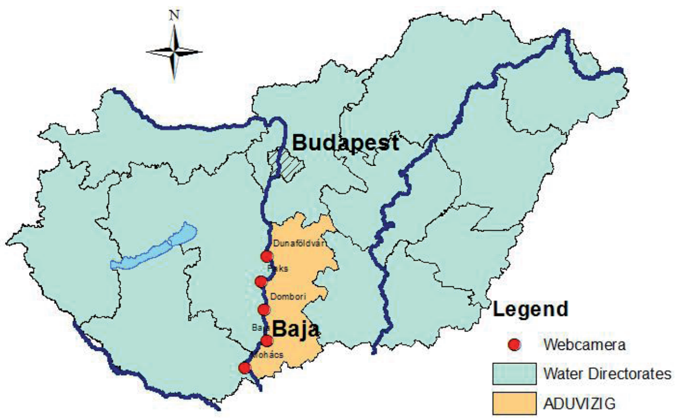

Fig. 5 Ice observer webcameras along the Danube in Hungary

The program provided a new and more comfortable way to investigate fluvial ice processes. In the past observers walking along the river bank could collect locally instantaneous, but less precise information about the processes. Now it is possible to watch the whole reach in real-time on-line remotely from the Water Directorate headquarters. Sufficient qualitative and quantitative information on the drifting floes along the monitored Danube reach were provided to the decision makers so as to prevent ordering redundant ice defense work, additionally field inspectors could be directed to the icy hotspots on the riverbank. This had a substantial economic benefit as ice defense is expensive: costs include fuel for the ice breaker ships and equipment preparation for ice defense. With the installation of the new cameras already during the first winter these costs were significantly reduced.

Since web-cam information goes straight on the internet the recorded images can be analyzed anywhere around the world. Experts can have real-time discussion, on the prevention of ice jam formation or opening of a developing one. Ice breaker ships can also be ordered.

Using even one single camera offers a huge advantage as the whole ice forming and melting period can be followed in the viewed section. Multiple cameras are of course even better so it is worth searching on the internet and find shared webcams. Once it happened that a city site camera in Budapest helped us to identify ice at that section of Danube. Now, with our distributed webcam system the situation is even better.

There are hotspots along the river where the floes could jam. Monitoring cameras could be placed at these locations as well. In addition, the monitoring system can provide high quality data at country border regions (Fig. 6), as it was done in 2012 with the Serbian partners. [4]

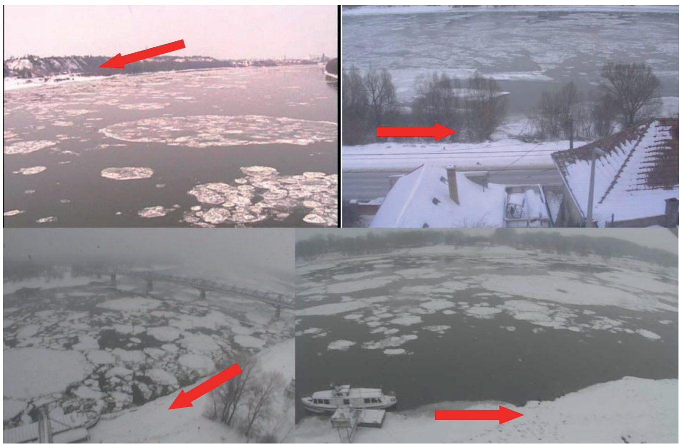

Fig. 6 Pictures of ice observer webcameras
(Dunaföldvár, Paks, Baja, Mohács 11/02/2012)

2.4 Camera-based ice monitoring in the world

Our river monitoring webcam system is not unique internationally but no doubt one of the earliest. By seeking the state-of-the-art of similar methods in the world there are some reported cases on the internet. For example the Mohawk River between New York State Barge Canal Locks is susceptible to ice jams. Ice jam related flooding can result from backwater associated with the jam or from water released downstream when a jam fails. Majority of historic Mohawk River floods in Schenectady have been associated with winter snowmelt and associated ice floes. Experts installed monitoring river elevation at four stream gages and a web camera was installed at the fifth location, between the investigated gages.

Another hot spot in the USA is situated on the Kennebac River. The web cam on the Kennebec River at Augusta serves as a continuous visual representation of the status of the river in the most flood prone river reach in Maine. The web cam both confirms the stage being reported from the gage, as well as it provides a unique real-time view of the ice processes in the river.

Ghobrial, Loewen and Hicks [25] described an algorithm that has been developed to process field data from two upward looking sonars, a current profiler and a monitoring station, to measure surface ice characteristics on the North Saskatchewan River (Canada), during the 2009/2010 freeze-up season. The algorithm used to calculate pans/rafts drafts and lengths, and the surface ice concentration is described. They suggested additional visual observations (e.g., time lapse photography) of surface ice conditions are recommended to aid in the interpretation of sonar measurements.

These early techniques have to be further developed particularly at those sites of the world, where the fluvial ice can cause serious environmental disasters. At these days our system shows the same novelties as the worldwide spreading partners, but our surplus is the 15 years old operational experience.

3 Meteorological conditions of the 2012 validation study

The most characteristic condition for ice formation along this Danube reach is when cold air arrives from Siberia and cools down the Carpathian basin. This was the case in February 2012 during the latest cold period when the Danube started to freeze. The macrosynoptic picture of this period is shown in Fig. 7, where the average air pressure map of the two-week-long period can be seen. At the end of January a large anticyclone formed from Siberia to Spain and the effect of the cyclone was significant in the Mediterranean region. The edge of the two effects met at Hungary and made a strong East, North-East stream. This kind of stream is not common since western winds are dominant in our country. The duration of the cool air transportation period was long. The Carpathian mountains could protect the basin against the cold air for only a few days, and by the end of January the daily temperature dropped under zero. Only the lack of snow reduced the cooling during nights. On February 3 the southern part of Hungary was reached by a wet air mass and caused significant snowing. The 30–40 cm deep snow cover and the windless, clear, unclouded nights caused the minimum temperature to drop under -20 ºC for 10–14 days. From 16th of February a slow warming period started. Similar weather situation occurred in January 1985 when the southern reach of the Danube was frozen for 3 weeks. Seeing the meteorological conditions it was predicted that after 22 years the Danube will freeze again in 2012, as it happened in Serbia. This did not happen finally, but may have occurred with 70–80 cm lower water levels and one more day below -15 ºC. Longer periods of freezing temperatures were not frequent in the last decades, but it is reasonable to assume that a more persistent and cooler situation can also happen.

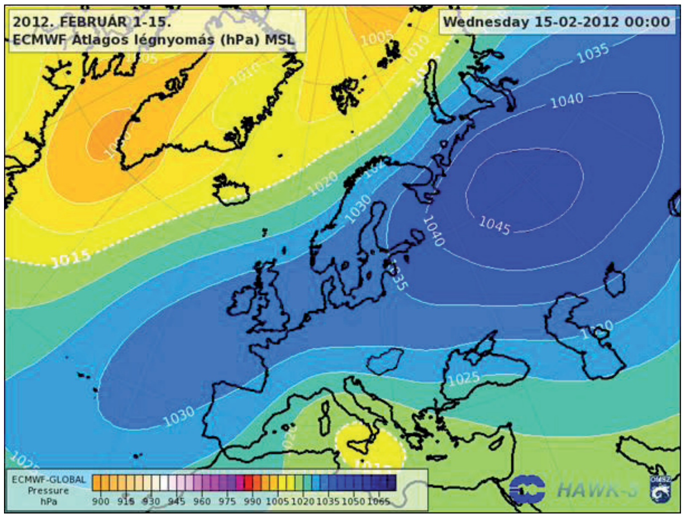

Fig. 7 Macrosynoptic situation in the first week of February 2012 (Kolláth Kornél, OMSZ)

4 Utilization of gained experiences

Using even a single camera offers a huge advantage vs sightings as the whole ice forming and melting period can be followed in the viewed section. Multiple cameras are of course even better. Even without the distribution monitoring system described in the previous sections, the feeds of public webcams on the internet can provide useful information for river ice dynamics. We mention one case when a camera in downtown Budapest helped us to identify ice at that section of Danube.

4.1 Characteristics of drifting floe

According to our experience there are mainly three types of drifting floe at the Baja section of River Danube.

In the first case a long reach of the river freezes at the same time. This type of freezing results huge (of the size of a football field), thin and sharp-edged floes. These big floes soon break apart by crashing bridge piers or river training works. The waves generated by the ships can destroy these ice floes. Waves induced by the wind can also crumble the ice, since these large floes occur mostly early in the morning after a calm cold night. The calm but chilly weather can freeze the supercooled water over large surfaces.

In the second case the ice forms in the river bed [23]. It can be either river bottom ice or floes detaching from the bank. In this situation the floes are not always flat, but under the water they are cone-shaped. Naturally freak forms and colors can be also present. The color depends on the material where the water froze. Buoyancy force and turbulence can lift the ice mixed with river bed sediment from the bottom but not able to keep it on the surface for long. These ice blocks flow near the thalweg and can seldom be seen on the surface.

In the third situation the floes form in the upper reaches of the river or its tributaries. The floe sizes are heterogeneous. Since they bump into each other debris ice form along the

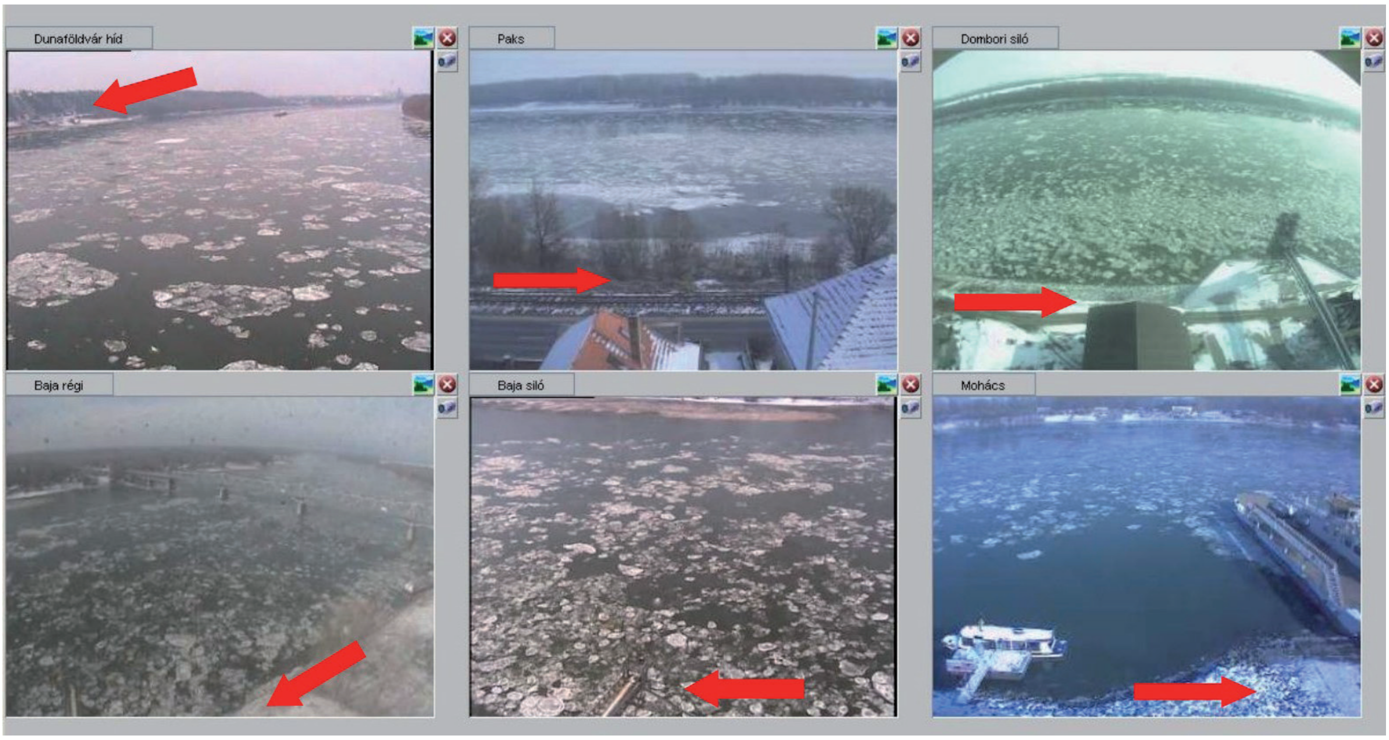

Fig. 8 Summarized picture of the webcam system. Six pictures were taken at six different sections of the river at the same time. From left to right and from top bottom the images represent the downstream order of flow locations.

edges. These small broken ice pieces originate from the great number of crashes between floes. Big floes are not flat because they are usually formed from the coalescence of small floes.

In Fig. 8 the third case of the floe formation is presented. Upstream the floes are big (top left) and at the last downstream location (bottom right) they are already broken into pieces and almost disappear. The distance is 120 km between these two sites. As the river moved downstream the ice met warmer weather.

Ice can form in any combination of the described three basic types. The distinction of these three types can help to classify ice phenomena and can lead us to make accurate forecast for them.

As we wrote, in the Hungarian water management practice the drifting floe is characterized primarily by surface area of the ice to the surface area of river as a percentage. From the recorded movies it is clear that the distribution of floes changes dynamically in time. It has a daily and even a shorter fluctuation. The drifting has got the same space-time characteristics as the stream velocity. As traditional velocimetry in a measurement point uses a continuous recording of at least 1 minute, the floe observation could be handled in the same way.

Next, the observer usually views the river from a lower elevation and is not able to distinguish stopped ice from the moving one, which could easily lead to an overestimation of the drift flux. For this reason automatic image processing of the pictures of webcams is recommended. Based on this process hourly statistics can be done providing more acceptable results.

4.2 Study of the hydrodynamic conditions

After installation of the new cameras few specific hydrodynamic cases were recorded and investigated. The collected information was summarized in a table where the rows represented the camera locations and the columns showed time. With no exception, in all the sections a daily periodicity was detected. Drifting in the morning was always more intensive than in the afternoon.

Uniform distribution of floes in the investigated sections occurred very seldom, mostly the main stream conveyed the ice pieces downstream. But in some cases the drift changed its structure and from one side of the river it moved to the other side. The main stream follows the concave bank as was expected, and floes are advected here in most of the time. Though the reason is not exactly clear, in certain cases the floes moved just at the convex bank. There were cases when there was near-shore ice on both sides in the same manner, and nothing was seen in the middle of river. Then, due to a strong westerly wind, the whole investigated reach drifted the ice on its left bank side.

Ships or ferries waiting in front of the cameras also formed an obstacle against drifting floe. An arched jam developed suddenly and helped to investigate this process. This real phenomenon could help us understand the developing stage of ice jams, to formulate the defence against them and to model all this complexity.

4.3 Modelling

Based on new webcam images, first validations of a model for ice-flow interaction could be performed [13]. The next picture (Fig. 9) shows a simulation area representing the section observed by our first webcam.

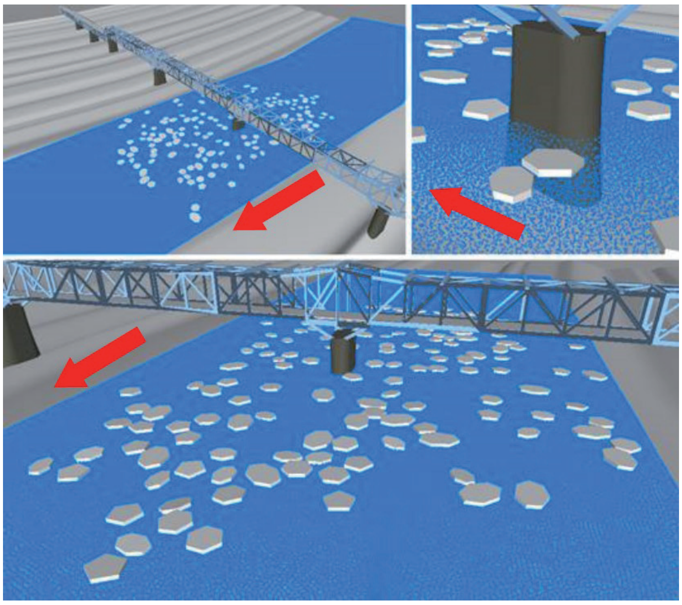

Fig. 9 High resolution simulation of the ice flow, reproduced from [13]

This smooth particle hydrodynamics (SPH) model, developed by Gábor Kiss, resolves many details with a high particle count for water (1.25 million), and 100 prismatic solid objects for the ice floes, and a complex bridge model with river bed, in a restricted area. These simulations were accelerated by parallel computing.

4.4 Discharge estimation

Marian Muste from Iowa University helped to analyze the very first pictures of our webcam. He also investigated the effects of river confluences on ice forming especially jam evaluations [14].

Vuyovich et al. [15] also studied how webcameras can be used to investigate river ice processes. Hourly images were taken over three winters at the confluence of the Allegheny River and Oil Creek in Oil City. Each image was manually processed and classified according to surface ice conditions. This laborious analysis has to be automated as much as possible.

Kerék [16] transformed the perspective view of our webcam images taken on 11st February 2012. He used coordinates from Google Earth as snap points recognized on both images. The orthorectified images of our webcam and the calculated surface velocity vectors can be seen on Fig. 10. The orange line crossing the section is the area where the surface velocity distribution was calculated. By knowing the cross section data across the orange line and the relation between surface and section average velocity the discharge could be determined.

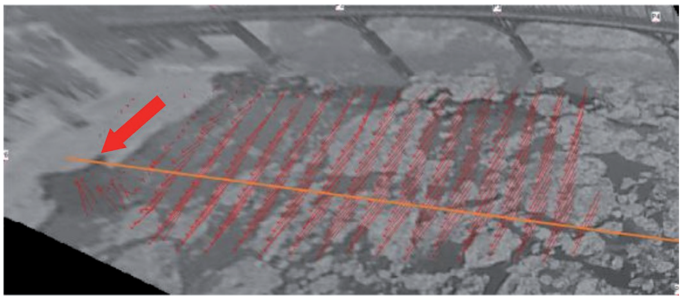

Fig 10 Calculated LSPIV surface velocity field on Danube at Baja 11/02/2012 [17]

The calculated discharge overpredicted the reference value (obtained from the calibrated discharge rating curve of the section) by 15%. This is more than the acceptable error in discharge measurements, but if we take under consideration the uncertainty of information used for this first calculation this result is promising. For this reason this research will be continued.

The drifting processes can be investigated by marking floes with an environmental friendly dye, since it is easier to identify the painted floe on the pictures. Drifting speed and path could be monitored between webcams. [17] The dye can be introduced from bridges.

A method is still needed to measure floe depth at least in a semi-automatic way. Presently, it is measured from a ship and it is hard and too slow. The thickness of ice is a necessary data to calculate the volume flux of ice.

By implementing all the above mentioned techniques, an automatic ice warning system could be established. Such a warning system could borrow ideas from security CCTVs (closed-circuit TVs) that are used at airports, for example. Here a software detects suspicious activities by checking the difference between a sequence of camera pictures and warns the guards if a luggage is left alone [17].

4.5 Ice forecasting

A lot of conditions influence the ice forming on the investigated reach of Danube. Beyond the previously mentioned conditions anthropogenic impacts affect the ice phenomena. These effects include discharges of waste water treatment plants and cooling waters of thermal power plants. The thermal plume of the Paks nuclear power plant, located 30–40 km upstream from Baja, is responsible for most of the melting of the blocked ice [2]. The first webcam was installed at this location.

Hirling [18] developed a simple ice forecasting method for the Hungarian rivers. The method calculates the cumulative sum of negative daily average air temperatures. This is a reasonably good method, but for some cases the occurrence of ice is not only a function of the local temperature. At Baja approximately -70 ˚C negative cumulative sum of air temperature and river water temperature below 0.5 ˚C must prevail to produce ice. The negative sum must contain temperatures cooler than

-5 ˚C. If the daily average temperature is higher than -5 ˚C no ice occurs even at a higher negative sum.

In some cases there are floes which formed in upstream tributaries of the river or released from reservoirs. It is not yet possible to forecast this kind of drifting. Upstream barrages on river Danube have got their own operational rules. They generally release ice from the upstream part at melting or breaking-up time. These kinds of floes slowly disappear while moving downstream.

Air and river water temperature data are usually accurate enough to do calculations and forecast the probability of ice occurrence or the extent of ice formation. Hopefully, these methods could be further improved by using webcam records from a longer river reach.

Forecasting of ice occurrence on the Danube was not as interesting as to predict the congeal. Due to our earlier experiences on 8th February 2012 (Fig. 11), we dared to forecast 90% coverage of floes or ice-up with the same probability. The latter case was estimated to have a two-day duration. At that time, everyone believed that the Danube will be fully covered by ice for a longer time period. The forecast that was issued (in Hungarian) is shown on Fig. 10. The disappearance of ice from the section was accurately predicted 11 days in advance.

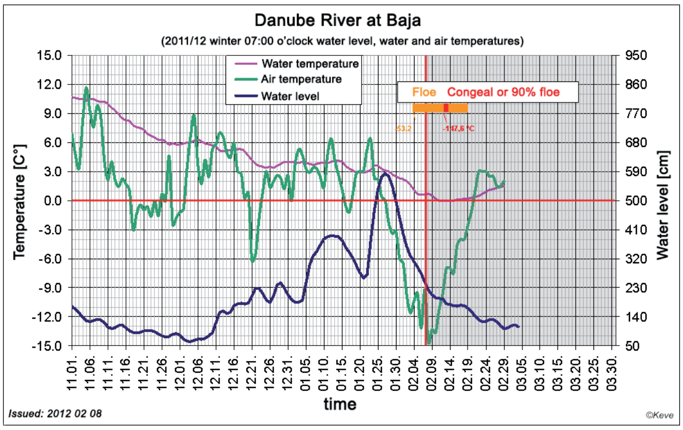

Fig. 11 Ice forecasting made on 8th February 2012. The blue line is water level, green is air temperature and magenta is water temperature. The orange strip represents the period of ice flow and red is the freezing period. The vertical red line separates the past and future events on the graph.

5 Ice thickness measurement procedure on the Danube

In Hungary, monitoring of surface waters and ice is regulated by two Technical Directives published in 2007. These directives regulate only the implementation of measurements. They do not however identify the conditions under which the measurements must be done. This is why no actual measurements of ice thickness are taking place on the Danube and only estimates are being used.

ME-10-231-07 Directive [19] concerning observation of ice phenomena on surface waters regulates the estimation of ice coverage and thickness. This directive distinguishes two kinds of visual estimation methods:

- point measurement: from a certain location of the bank (usually at water gauges)
- linear measurement: visual observation by walking along the river between given sections

Estimation of ice coverage is proposed to be replaced by webcam-based observations and subsequent quantitative analyses.

According to our experience, visual estimation of ice thickness is hindered by unexpectedly high errors and yield little useful data. This was the reason for releasing the second directive:

ME-10-231-08 Directive [20] Ice thickness measurements on surface waters. Based on previous regulation most of the methods and standards were out-of-date or difficult to follow. The equipment for measurement is not specified and, if so, nearly impossible to use in winter conditions. And finally, the directive states: "If the conditions for measurements are not safe enough, the ice thickness must be estimated". Due to this, measurement conditions are always considered dangerous on rivers and estimation was the final solution.

The first task was to develop a simple device to measure ice thickness quickly and reliably. The Directive [20] offers a schematic for a staff (Fig. 12), but it cannot be used for drifted floe. Its moving parts freeze up when it is first submerged and it can measure only the edge of the ice. However, the drift-ice surfaces are not flat with its sides under and above the water are nonuniform. Measuring the thickness to centimeter accuracy is pointless under these circumstances [4].

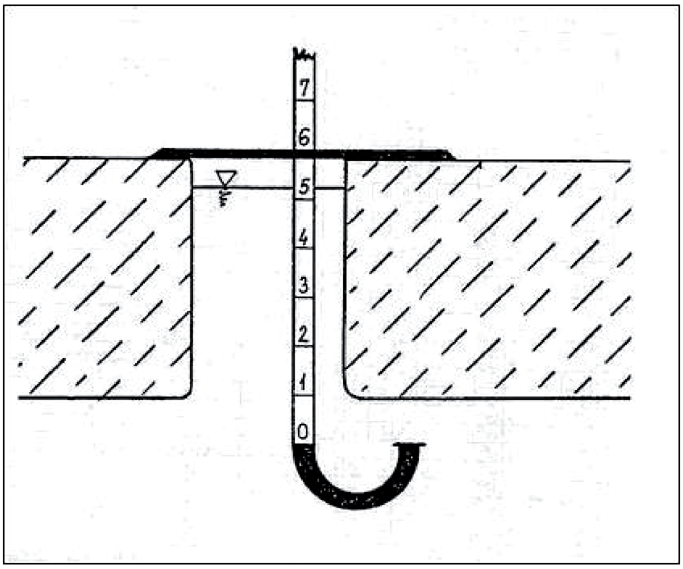

Fig. 12 Theoretical schematic of ice staff [20]

The Keve-staff (Fig. 13) was developed to solve some of these problems. It has been tested and provides a useful cheap tool for measuring ice thickness. The device is fabricated from a finished roof batten. The vertical segment is 3 m to which a 1,5-long horizontal piece joins (with extra reinforcement) with a wing-nut. The device is easily dismounted for transport. It works like a caliper with only one side to the jaw. The water level is used as a reference for measuring the thickness of ice below water and the thickness above. Ice thickness is then the sum of these two measurements. Measurement scales (10 cm graduations) on the device are accurate to within 5 cm. The same interval is applied when we measure the diameter of floes using a horizontal staff. The 1,5 m length lets us reach the bottom of the floe far from the edge where it may be thicker.

The measurement is fairly simple (Fig. 14). First we place the horizontal part of the staff on the top of the floe (14a) and try to keep it straight and read the thickness of the floe above water. Next we submerge the staff under the floe and let its buoyancy lift up the horizontal segment until it touches the bottom of the floe, thus measuring the thickness below the water level. The sum of two readings gives us the ice thickness.

It is recommended to estimate the diameter of floe (by using a horizontal scale) and determine the shape of ice as well (round, oval, polygon, etc.) then record all data on a report sheet. We experienced cases when the official (estimated) ice thickness was 20 cm while our measured thickness averaged a substantially higher 75 cm [4]. In order to improve temperature measurements as well, they should be taken at similar locations and verticals as the thickness measurements.

ME-10-231-09 Directive [21] about “Measurements of surface water temperatures with ladle thermometer” is also out of date. There are almost no ladle thermometers in hydrometrical practice, but there are new thermo-sensors. With these new types of sensors, both sectional and vertical measurements should be taken.

Hydrological handbooks [22, 23] describe the fluvial cooling method as a turbulent process rather than as horizontal thermoclines seen in lakes. We have not measured the sectional thermal distribution during the cooling process yet, but we did measure temperatures under ice phenomena. Using a long wooden stick, the sensor was submerged 1,5–2 m depth in 30 cm steps.

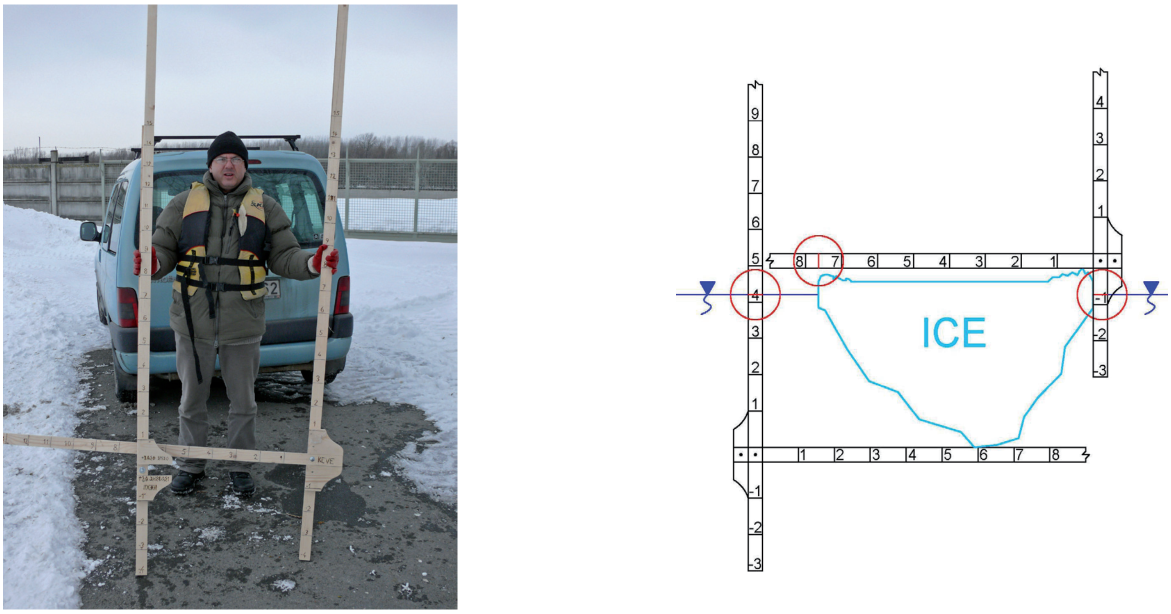

Fig. 13 Keve-staff (closed and opened on the left, theoretical schematic on the right)

Fig. 14 Measuring ice thickness above (a) and below (b) water level on the Danube

Fig. 15 Captured and overturned floe

These measurements were taken at the vertical profiles of ice thickness measures. Our experience is that there is no significant difference along the vertical depth, but between separate vertical profiles variation exists. There seems to be no equilibrium temperature along the sections investigated. The vertical profiles without ice on the surface were sometimes significantly warmer than the covered profiles and it contradicts predictions from turbulence theory. The effect of thermal load originated from an upper power plant (Paks) is not such significant at this section. [24]

6 Conclusions

The weeks-long prevailing ice period was successfully recorded by our webcams at 5 sites along the Danube. Coupled with morphological and hydro-meteorological data, a preliminary analysis showed the potential to derive space-time characteristics of the floating ice: size composition, motion and rearrangement due to secondary currents, and occasional packing/release at places. The experiences gained have opened new ways of thinking and we were able to introduce new techniques such as discharge estimation, ice thickness measurements, etc.. Efforts to quantify the above mentioned features and improve recording quality are underway. Webcam monitoring can be a very beneficial experience for which new ways of observation and investigations have been implemented.

However the Hungarian Hydrometric Service still works with somewhat outdated methods, which lack elementary data to understand these phenomena and are difficult to implement. It was believed that floes are flat and they were modelled that way. However, our measurements showed that they are sometimes tapered (Fig. 15). Turning over the floes revealed this to be true.

We observed vertically uniform temperatures in an ice-covered cross section but horizontal temperature differences were notable. The reasons for this are not clear, but this phenomenon must be investigated in more details as it highly affects ice formation.

The most important needs for improvement to help avoiding serious ice floods are the following:

- Install webcams along our rivers and develop automatic image processing to determine ice coverage and characterize all sections by reliable, objective methods. This should be extended for international river sections with common interests.
- To follow the behavior of ice, air reconnaissance has a great advantage. Recently altered river bed morphology gives us a chance to model and recognize the critical spots for ice accumulation. We could prepare for more frequent checking of these crucial places using aerial methods (drones). For greater effectiveness, we need more knowledge about ice phenomena too.
- Maintaining the ice breaker ships is a permanent duty but this has been neglected for a while before February 2012. Using them for ice measurements would not create extra cost, as the ships must be kept warm during cold periods anyway.
- Ice thickness and water temperature measurements must be performed in a standardized and reliable way. The so called Keve-staff is useful but a more up-to-date method should be found.
- Most of the river gauges are telemetered and equipped with thermal sensors as well. Installing further gauges between the existing ones would help to pinpoint rapid changes in water levels providing a reliable precursor to ice jams without requiring good visibility.

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References

[1] Lászlóffy, W. "A folyók jégviszonyai, különös tekintettel a Magyar Dunára." (Ice conditions in rivers, in particular in river Danube in Hungary.) *Vízügyi Közlemények*. 16(3), pp. 369-435, 1934. (in Hungarian) URL: http://apps.arcanum.hu/app/vizugyi/view/VizugyiKozlemenyek_1934/?query=SZO%3D(l%C3%A1szl%C3%B3ffy)&pg=466&layout=s

[2] Keve, G. "Jégmegfigyelések korszerűsítési lehetőségei." (Improvement and up-to-date development of ice observations.) *Vízügyi Közlemények*. 84(3), pp. 358-378. 2002. (in Hungarian) URL: http://apps.arcanum.hu/app/vizugyi/view/VizugyiKozlemenyek_2002/?query=SZO%3D(Keve)&pg=367&layout=s

[3] Starosolszky, Ö. "A jégjelenségek és a hazai folyók jégviszonyai." (Ice phenomena and ice conditions in the Hungarian rivers.) In: *Árvízvedelem.* (Zorkóczy, Z. ed.) pp. 104-116., Országos Vízügyi Hivatal, Budapest. 1987.

[4] Keve, G. "2012. évi dunai jégészlelés tapasztalatai." (Experiences of ice measures in 2012.) Summary documentation, ADU-NeKI, 2012. (in Hungarian)

[5] Zsuffa, I. "Hidrológiai mérések: Jégészlelés." (Hydrological measurements: ice observation.) Vízügyi Műszaki Segédlet, VMS 231/6-T/78.01/ G70.1978. 1978. (in Hungarian)

[6] Zsuffa, I. "*Műszaki hidrológia*." (Applied hydrology.) Tankönyvkiadó. Budapest. 1984. (in Hungarian)

[7] Keve, G. "Danubian ice observation by webcameras." *Riscuri si catastrofe*. 9(2), pp. 191-204. 2011. URL: http://riscurisicatastrofe.reviste.ubbcluj.ro/Volume/X_Nr_10_2011/PDF/GKeve.pdf

[8] Jasek, M. "LSPIV and Numerical-Model Estimation of Yukon River Discharge During an Ice Jam Near Dawson." Iowa University, 1999. DOI: 10.1139/cjce-28-5-856

[9] Ettema, R. "Review of Alluvial-channel Responses to River Ice." *Journal of Cold Regions Engineering*. 16(4), pp. 191-217. 2002. DOI: 10.1061/(ASCE)0887-381X(2002)16:4(191)

[10] Kimura, Y., Iida, S., Mori, H. "River flow information system with RF current sensors." In: 21st International Conference on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, San Diego, Jan. 5-14, 2005. paper 10.8. URL: https://ams.confex.com/ams/pdfpapers/84651.pdf

[11] Sokoray-Varga, B., Józsa, J. "Particle tracking velocimetry (PTV) and its application to analyse free surface flows in laboratory scale models." *Periodica Polytechnica Civil Engineering*. 52(2), pp. 63-71. 2008. DOI: 10.3311/pp.ci.2008-2.02

[12] Gálai, A. "River Ice Inspection by Webcameras, Basics." ULR: http://www.water.hu/ice/webcam/index.php?en

[13] Kiss G. "Mozgó komplex objektumok vizsgálata háromdimenziós folyadékszimulációs környezetben." (Three-dimensional flow modeling with complex moving-object interactions.) BSc final project report, Budapest University of Technology and Economics, Faculty of Civil Engineering, *Hidrológiai Tájékoztató*. 1, pp. 24-25. 2014. (in Hungarian)

[14] Ettema, R., Muste, M., Kruger, A. "Ice Jams in River Confluences." CR-REL Report, US Army Corps of Engineers, p. 61. 1999.

[15] Vuyovich C., Daly, S., Gagnon, J., Weyrick, P., Zaitsoff, M. "Monitoring River Ice Conditions Using Web-Based Cameras." *Journal of Cold Regions Engineering*. 23(1), pp. 1-17. 2009. DOI: 10.1061/(ASCE)0887-381X(2009)23:1(1)

[16] Kerék, G. "Applicability of video-based flow measurements in small streams." MSc thesis, Budapest University of Technology and Economics, Faculty of Civil Engineering, 2015.

[17] Keve, G. "Space-time ice monitoring of the river Danube in Hungary by multiple web-cameras." Riverflow2010. International Conference on Fluvial Hydraulics, Sept. 8-10, 2010, TU Braunschweig, Germany. 2010.

[18] Hirling, Gy. "Forecast of the ice phenomena in river Danube and Tisza." VIZDOK. Budapest., 1981. (In Hungarian)

[19] ME-10-231-7. "Felszíni vizek jégjelenségeinek megfigyelése." (Observation of ice phenomena on surface waters.) Vízrajzi mérések végrehajtása. 2007. (in Hungarian)

[20] ME-10-231-8. "Felszíni vizek jégvastagságának mérése." (Ice thickness measurements on surface waters.), Vízrajzi mérések végrehajtása. 2007. (in Hungarian)

[21] ME-10-231-9. "Felszíni vizek vízhőmérsékletének mérése merítőedényes hőmérővel." (Measurements of surface water temperatures with ladle thermometer.), Vízrajzi mérések végrehajtása. 2007. (in Hungarian)

[22] Németh, E. "*Hidrológia és hidrometria*." (Hydrology and hydrometry.) Tankönyvkiadó, Budapest. 1959. (in Hungarian)

[23] Chow, V. T. "*Handbook of Applied Hydrology*." McGraw-Hill Book Company, New York. 1964.

[24] Szolnoky, Cs. "Live question in the thermal load and thermal pollution of Hungarian rivers." *Periodica Polytechnica Civil Engineering*. 31(3-4), 121-137. 1987. URL: http://periodicapolytechnica.org/ci/article/view/3957/3062

[25] Ghobrial, T. R., Loewen, M. R., Hicks, F. E. "Continuous monitoring of river surface ice during freeze-up using upward looking sonar." *Cold Regions Science and Technology*. 86, pp. 69–85. 2013. DOI: 10.1016/j.coldregions.2012.10.009