JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2021.139037
2021, No. 51 (X–XII): 256–264

Concept and implementation of the Polish innovative agro-hydro-meteorological monitoring (AgHMM) in INOMEL Project

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RECEIVED 10.11.2021 REVIEWED 21.11.2021 ACCEPTED 11.12.2021

Abstract: The paper presents the concept and deployment of the agro-hydro-meteorological monitoring system (abbrev. AgHMM) created for the purposes of operational planning of regulated drainage and irrigation on the scale of a drainage/irrigation system (INOMEL project). Monitoring system involved regular daily (weekly readings) measurements of agrometeorological and hydrological parameters in water courses at melioration object during vegetation seasons. The measurement results enable an assessment of the meteorological conditions, moisture changes in the 0-60 cm soil profile, fluctuations of groundwater levels at quarters and testing points, also water levels in ditches and at dam structures, and water flow in water courses. These data were supplemended by 7-day meteorological forecast parameter predictions, served as input data for a model of operational planning of drainage and subirrigation at the six melioration systems in Poland. In addition, it was carried out irregular remote sensing observations of plant condition, water consumption by plants and soil moisture levels using imagery taken by unmanned aerial vehicles and Sentinel's satellites. All the collected data was used for support operational activities aimed at maintaining optimal soil moisture for plant growth and should to provide farmers with high and stable yields. An example of the practical operations using the AgHMM system in 2019 is shown on the basis of the subirrigation object at permanent grasslands located in central Poland called "Czarny Rów B1".

Keywords: adaptation, agro-hydro-meteorological monitoring system, climate change, controlled drainage, decision support system, short-term forecast, subirrigation, water management, water resources

INTRODUCTION

The progressing adverse climate changes result in Polish agriculture becoming increasingly dependent on meteorological conditions, and lead to an increased farmer interest in various kinds of advisory services. This form of knowledge assistance has gained popularity as a result of the progress in informatisation and telecommunication, which enables finding the desired information from any location in the country. Gradually, the idea of Stigter *et al.* [2010], that advice services for farmers should become a permanent aid in the decision-making process and in field work planning, while current weather condition monitoring and early warning should assist in actions intended to mitigate the adverse consequences in agriculture caused by weather phenomena and climate changes, is becoming reality.

One of the forms of informing society about agro-hydro-meteorological conditions in Poland are specialised services that utilise data from systems monitoring various parameters of the atmosphere, soil, and water environment. The necessity for such sources of information arises because of the climate change observed in the last 40 years in Poland, manifested in the form of changes in precipitation distribution during the year, which have led to a situation where most of the country agricultural area suffers from a precipitation deficit and increased occurance of weather extremes [Grzywna *et al.* 2020]. Due to the low average annual total precipitation amount, Poland is in the last ten of the

46 European countries, and total water resources (per capita) in Poland are less than half those of Hungary or France [Mioduszewski, Dembek 2009]. At the same time, at approximately 60% of Poland's surface area, precipitation is the main water source for arable land and permanent grasslands [Mioduszewski *et al.* 2011]. While occasionally periods of increased precipitation do occur, causing in temporary flooding of fields and environmentally harmful oxy-reduction processes [Ostrowski, Łabędzki 2016] or also hampering field work, these phenomena have become rarer than droughts in recent decades. In many parts of Europe, especially in the south and in the middle of the continent, yet since 1970s a gradual increase of number of droughts has been observed [Bordi *et al.* 2009].

A systematic increase numbers of websites dedicated to agriculture advices are being observed in Europe and their content is gradually expanding [Dyer, Lally 1990; Leśny *et al.* 2007; Łabędzki, Bąk 2015a; USGS 2019]. In Poland, the most important website for farmers is Agricultural Drought Monitoring System (ADMS), maintained by the Institute of Soil Science and Plant Cultivation State Research Institute (IUNG). The purpose of this website is monitoring agricultural drought in Poland [ADMS undated]. Another system is the Operational System for Providing Drought Prediction and Characteristics (AGROMETEO), provided by the Institute of Meteorology and Water Management – State Research Institute (Pol. Instytut Meterologii i Gospodarki Wodnej – Państwowy Instut Badawczy – IMGW – PIB) [AGROMETEO 2020]. These two websites are complemented by an agricultural drought remote sensing service based on satellite images which operates at the Institute of Geodesy and Cartography – (IGIK) [IGIK undated]. In addition to these services, polish farmers can also access European services, such as Monitoring Agricultural ResourceS (MARS) bulletins (MARS) [JRC MARS undated] and European Drought Observatory (EDO) and European Drought Observatory (EDO) [EDO 2020].

The adverse atmospheric conditions that cause periods of insufficient precipitation and drought, necessitate rational use of water in agriculture. While the observed and predicted multi-year trend of annual precipitation totals is almost constant, seasonal precipitation distribution in time is becoming increasingly irregular. According to different climate scenarios, the risk of meteorological, agricultural and hydrological droughts in Central Europe will increase [IPCC 2018]. For the above reasons, monitoring of irrigation and drainage melioration structures in Poland is becoming particularly important, as it is required to provide more detailed information of agro-hydro-meteorological conditions at the scale of a melioration object [Łabędzki 2016]. Based on the experience gathered in European countries, it can be concluded that among many activities aimed at adaptation to climate change, the creation of systems for data gathering supporting water management is one of the most important [Kovalenko *et. al.* 2019; Massey 2012]. The issue is particularly important when meteorological factors are characterised by very high spatial variability and significantly impacting pedoclimatic and hydrological conditions. Analysis and predictions provided by the aforementioned websites are too general for the purposes of detailed monitoring particular melioration objects. This is particularly visible at larger melioration objects, which are characterised by significant soil variabilities, terrain conditions and differnt impact this melioration systems on permanent grasslands or crops. In such cases, more detailed data concerning the local distribution of precipitation and other meteorological factors as well as moisture in soil profiles, and groundwater and water levels at different locations in a melioration system are needed. Additionally at subirrigation systems it is useful to know the water levels and water flow rates in water courses and ditches.

In 2017, reclaimed arable land in Poland took up an area of 6370 thous. ha, which is approximately 44% of the total arable land area. Drained arable land had an area of 3973 thous. ha, while land adapted for irrigation – 47 thous. ha. For grasslands and pastures, these values were 411 thous. and 375 thous. ha, respectively [GUS 2019]. Unfortunately, melioration infrastructure maintainance in Poland is not satisfied. The number of melioration systems which operated properly and fulfill effectively their drainage or irrigation functions have been decreasing from year to year. It is caused by the poor technical condition of many individual melioration installations, lack of regular maintenance, as well as due to discontinued operation of certain melioration systems, in particular those at permanent grasslands [Kaca 2014; Kiryluk 2014].

To deal with above mentioned problem, an interdisciplinary consortium composed of research entities and small enterprises was created to develop and prepare for implementation a system of monitoring and operational planning of regulated drainage and subirrigation on the scale of melioration object. The whole system, supported with remote sensing and short term weather forecast, is also equipped with innovative, developed within the project, devices for regulating water outflow from the object, as well as regulating and measuring water inflow taken for irrigation.

The aim of the study is to present the concept of an innovative agro-hydro-meteorological monitoring system (abbrev. AgHMM) [Kaca *et al.* 2020], developed within the INOMEL project [Łabędzki, Kaca 2017]. The AgHMM system is a part (entry module) of the whole system for monitoring and operational planning irrigation and dranaige. The concept of the system is presented on the example of one amoung six melioration objects selected for the project. The object is situated in the northern part of central Poland.

The AgHMM provides information on the status of groundwater and water in ditches, information on water flows in watercourses feeding the object (for forecasting water flows in watercourses), information on soil moisture and information on weather conditions (initial conditions for calculations). The information collected by the system are used for forecasting of the conditions on a melioration object which are necessary in operational planning of irrigation and drainage.

Observed significant spatial and temporal variability of precipitation recently, cause development excacly such system which will allow on optimal management of the limited resources of water used for irrigation and stopping uncontrolled runoff.

STUDY MATERIALS AND METHODS

Seeing the need for creating such a monitoring system, the consortium of Polish research institutions and private businesses submitted the INOMEL research project in 2016 [Kaca *et al.* 2016]. The authors of the project recognised a need for using the results of ongoing agro-hydro-meteorological measurements at the melioration system, supplemented with a 7-day meteorological forecast for the purposes of modelling and managing water at the melioration system on consecutive days during the forecast. It was assumed that the operational model would contribute to maintaining the optimum vegetation conditions at permanent grasslands throughout maintaining the level of soil moisture at which high yields of hay are achieved. This problem is especially important during periods of drought and excessive precipitation.

The INOMEL project research consortium was formed by: Institute of Technology and Life Sciences as the leader, Warsaw University of Life Sciences, Wrocław University of Environmental and Life Sciences, Poznań University of Life Sciences, Geofabryka Ltd., Agrocom Polska Jerzy Koronczok.

Preparatory works for creating such a system were preceded by numerous studies of various pre-existing agricultural monitoring systems in Poland and abroad. In Poland, the first attempts at monitoring a melioration system for the purpose of controlling water were made in the 1990s. in the Upper Noteć River area [Kaca 1999; Kaca, Łabędzki 1995; Kaca *et al.* 2001]. Another example of a more comprehensive agro-hydro-meteorological system and an advice website was a project conducted in 2011–2015 at the Institute of Technology and Life Sciences under the name "System for monitoring and prediction of moisture conditions in agricultural ecosystems". Using a country-wide meteorological station network, maintained by the IMGW, water deficits and excesses were monitored in selected regions of Poland. Based on the monitoring data, mathematical modelling and using indices of the meteorological drought *SPI*, agricultural drought *CDI* (Crop Drought Index) and soil moisture drought *SMI* (Soil Moisture Index), the impact of meteorological conditions on the yields of selected field crops and permanent grasslands in different climatic, soil and water environments were determined [Łabędzki, Bąk 2014]. An innovative element of the website was the weather forecast module (10 and 20-day), applied for the first time in Poland, used to calculate the predicted values of the above parameters. Monitoring and forecast results were shown online as maps, charts and tables [Łabędzki, Bąk 2015a; Łabędzki *et al.* 2013]. The experience gained in such operating monitoring system were partly used in the INOMEL project as well.

The AgHMM system, designed for the purposes of executing the INOMEL project is understood as a system of operational measurements, assessments and forecasts of agro-hydro-meteorological characteristics of drainage and irrigation systems using modern techniques of measurement and telecommunication and IT tools. The scope of AgHMM included innovative measurement methods of meteorological, soil moisture and water conditions on permanent grassland and agricultural lands, water conditions in ditches and canals and on damming structures. Meteorological forecasts in the next 7 days were also an element of the monitoring. It was supplemented by irregular remote sensing observations using images from the Sentinel's satellites and low-altitude flights by using drones and planes. It was decided that atmosphere, soil and hydrosphere environmental conditions will be monitored concurrently, and the measurement data acquired will be used as input data in the system-level precision water management system, as well as for operational planning of drainage and subirrigation.

A thorough review of Polish and foreign literature was done as part of preparing the AgHMM concept, too. The experiences of foreign scientific institutions was investigated, primarily for the measurement methodologies used, measurement instruments employed, and methods of designing measurement networks. Studies concerning wide-area monitoring systems, developed as early as the 1980s. in the USA and other countries, proved highly valuable [Bencini *et al.* 2010; Elgaali *et al.* 2007; Hamami, Nassereddine 2018; Kerkez *et al.* 2012; Nikolidakis *et al.* 2015; Ojha *et al.* 2015; Pfannkuch, Labno 1977; Wang, Balasingham 2010; Western *et al.* 2002]. Useful and practical know-how related to designing some elements of agro-hydro-meteorological systems was also provided by the consortium members, who had been involved before, to various degrees, in monitoring melioration systems in selected agricultural regions in Poland [Brandyk *et al.* 2018; Bykowski *et al.* 2005; Kaca *et al.* 2001; Kozaczyk *et al.* 2016; Łabędzki, Bąk 2015b; Oleszczuk *et al.* 2009; 2013].

Parallel to the activities of AgHMM, for another task in the INOMEL project, monitoring by remote sensing at selected research sites was planned. This type of monitoring have included periodic remote sensing observations using images from the Sentinel satellites and low-altitude images taken using unmanned aerial vehicles (based mostly on visual and short infrared waves). Images obtained in this way extended the knowledge of the environment's condition at melioration objects and took more time for interpretation, therefore they were not subject to regular exchange between the consortium members.

For each research object, independent historical meteorological databases were created, and soil and hydrological characteristics were prepared. Based on adopted research methodologies, the required measurement instruments were listed. A diagram of the AgHMM system with the short-term weather forecast module is shown in Figure 1.

The scope of the AgHMM at melioration systems covers monitoring meteorological conditions, soil moisture, measurements of flow rates in the main water course and the channels, measurements of water flow rates at the water intakes, outflow and hydrotechnical structures, as well as measuring water levels in ditches, ground water table levels at permanent grassland locations and agricultural croplands.

Meteorological monitoring assumes daily measuremets of meteorological elements using automatic weather station equipped in sonic anemometer for wind speed measurement, air temperature and relative humidity sensors, rain gauge and pyranometer for global radiation. The station was installed in the vicinity or directly at the research sites. This is supplemented by 7-day forecasts of daily values of the above elements, which are provided by the model COSMO utilised at the Deutscher Wetterdienst (DWD) in Germany, and implemented by the IMGW [Majewski *et al.* 2002]. The model is used to prepare operational numerical weather forecasts (NWP – Numerical Weather Prediction), with initial input data being taken from the global GME model (Generic Modeling Environment) [COSMO 2011; Ledeczi *et al.* 2001]. It should be noted that precipitation forecasts has the lowest reliability among the other weather elements [Kasperska-Wołowicz *et al.* 2019].

Agrometeorological monitoring of soil moisture is performed using profile probes, dual-level soil moisture sensors and manually using a portable TDR device. An additional source of information on current meteorological and agrometeorological conditions in the area of the sites are the daily weather

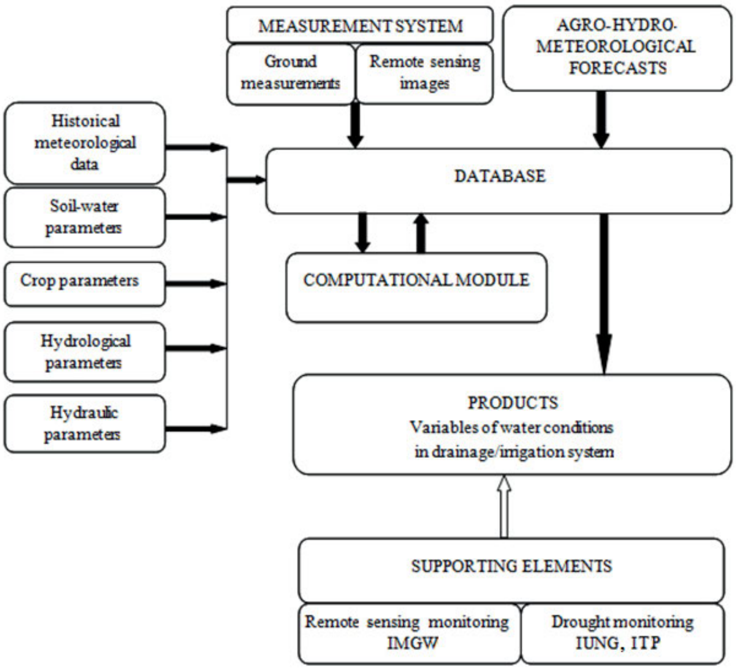

Fig. 1. A scheme of the system of agro-hydro-meteorological monitoring and short-term forecasting in irrigation/drainage systems; source: own elaboration

information and forecasts published in the Internet on the websites of Polish and foreign agrometeorological services.

The task of the hydrometeorological monitoring at the melioration systems is to monitor water resources available for irrigation. For this purpose locations for water flow rate measurements in surface waters in the main water course and in the ditches were defined. In the vicinity of existing water intake and outflow structures, as well as the projected regulators of water outflow from drained agricultural areas, sensors of upper and lower water levels (Levelogger model 3001, Solinst) were installed.

Hydrological monitoring at the designated permanent grassland locations covers measurements of water table levels at the locations of groundwater level sensors and locations of periodical groundwater level measurements. The data obtained enable determining the current status of soil retention and are entered into the prediction model as the initial state of the system at simulation start. Groundwater levels are measured by submersible pressure (Barologger model 3001, Solinst) and later these measured data are corrected on the basis on the atmospheric pressure values measured by the pressure sensors installed near the test sites. Direct measurements of flow rates are also performed using an inductive flow rate meter with a datalogger (Sensa Z 300, OTT Hydrometrie).

The tasks of the AgHMM system described above have performed at six research melioration objects in Poland. This objects were located in Mazovian Voivodeship (Grabów and Troszyn), in Kuyavian-Pomeranian Voivodeship (Smolniki, Kolonia Bodzanowska) and in Greater Poland (Wielkopolska) Voivodeship (Racot, Ostrowo Szlacheckie). The tasks have been performed in the entire measurement scope since June 2019 once the installation of hydrological measurement network was completed, with the scope depending on the local and technical capabilities at the individual object.

RESULTS AND DISCUSSION

THE AGHMM AT DRAINAGE AND SUBIRRIGATION MELIORATION SYSTEM CZARNY RÓW B1

One of the site where the AgHMM system was installed was subirrigation melioration system called Czarny Rów B1, supervised in the INOMEL project by scientists from the Institute of Technology and Life Sciences and the Warsaw University of Life Sciences. In the paper this object site is used as an example of how the AgHMM system was implemented in practice. This melioration system is located near the Szubin locality, 20 km south-west of Bydgoszcz, Poland. The Czarny Rów water course, an affluent of the Gąsawka River, flows across the site. Both the river Gąsawka and the Czarny Rów water course are sources of water used in subsurface irrigation of the permanent grasslands located at the site. During hydrological drought periods, Czarny Rów can be irrigate with water from the Gąsawka using a water supply ditch. The total area of the Czarny Rów site is over 200 ha, but its B1 section, where monitoring is conducted, has an area of 80.9 ha.

The predominant soil type are peat-moorsh on sandy formations, which belong to shallow organic soils. The average thickness of the peat-moorsh soils layer along the observation well line does not exceed 0.8 m. The predominant type of land usage at the site is grassland use, primarily 3 crops per year; in 2017–2019 the average hay yield was 8.9 $Mg \cdot ha^{-1}$. The map of the Czarny Rów B1 melioration system and locations of the measurement devices of the AgHMM system is shown in Figure 2.

AGROMETEOROLOGICAL MONITORING

Meteorological monitoring at the Czarny Rów B1 site was provided by an automatic weather station located in its northern part. Meteorological measurements were performed every

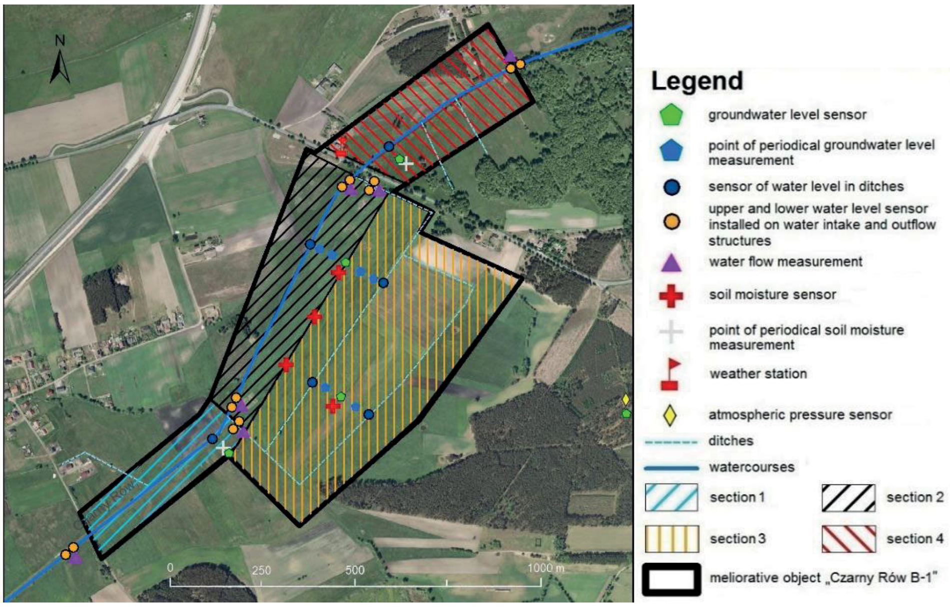

Fig. 2. Map of the Czarny Rów B1 melioration system and locations of the measurement instruments; source: own study

10 minutes and uploaded to the server once an hour. Furthermore, during the period from March to September, once a week, a 7-day forecast of meteorological parameters for this site, prepared by the IMGW – PIB, was received. The collected weekly meteorological data, together with forecast data, were sent in the form of a bulletin to the consortium members and to the team that have developed an irrigation and drainage decision models. An example of data presented in the bulletin is shown in Table 1.

The observed changes in meteorological parameters during the research period can be presented in the form of graphs. A sample chart of changes total precipitation levels and average day-temperature in week-long period from June to October 2019 are shown in Figure 3.

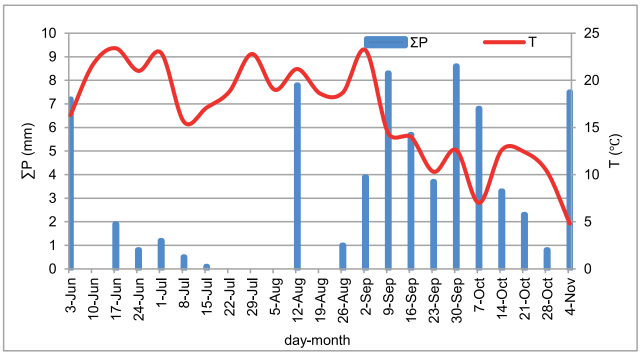

Fig. 3. Course of weekly total precipitation ΣP and average weekly temperature T in the period from June till November 2019; source: own study

Table 1. Daily (7-day observed and 7-day forecast) values of main meteorological parameters included in the bulletin (2019 year)

Observations							
Parameter	24 Sep	25 Sep	26 Sep	27 Sep	28 Sep	29 Sep	30 Sep
P (mm)	0.0	0.2	0.5	3.5	0.3	1.1	3.0
T (°C)	8.3	11.9	13.4	13.7	13.9	14.1	13.1
f (%)	98.6	94.9	92.0	97.1	92.4	90.7	95.4
R_a (W·m^{-2})	48.9	58.6	71.8	63.1	70.6	64.1	26.8
v (m·s^{-1})	0.7	0.5	0.4	1.5	2.4	3.6	3.5
Forecasts							
Parameter	01 Oct	02 Oct	03 Oct	04 Oct	05 Oct	06 Oct	07 Oct
P (mm)	0.1	1.2	0.0	1.3	0.9	0.0	0.0
T (°C)	14.5	14.5	14	13.8	13.6	13.8	13.7
f (%)	73.2	81.6	85.3	87.7	79.2	71.2	71.6
R_a (W·m^{-2})	157.8	42.4	79.6	55.9	136.4	101	158.5
v (m·s^{-1})	3.1	2.0	0.9	3.5	4.0	5.2	5.1

Explanations: P = precipitation, T = air temperature, f = air humidity, R_a = solar radiation, v = wind speed.
Source: own study.

Monitoring of moisture in soil profiles was conducted using soil moisture profile probes (ADCON Soil Moisture Probe SDI-12), which enable measurements at depths of 10, 20, ..., 60 cm, and soil moisture sensors (WaterScout SM100) at two levels: 20 and 40 cm. An example of soil moisture changes (Volumetric Water Content, VWC, in %) at levels: –20 cm (S1) and –30 cm (S2), recorded with the ADCON probe at peat-moorsh soil is shown in Figure 4.

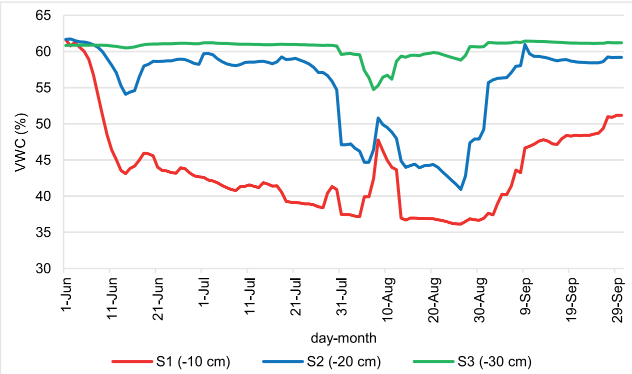

Fig. 4. Soil moisture changes at levels: S1 (–10 cm), S2 (–20 cm) and S3 (–30 cm) recorded by ADCON probe at peat-moorsh soil (VWC, %) in the period from June till September 2019; source: own study

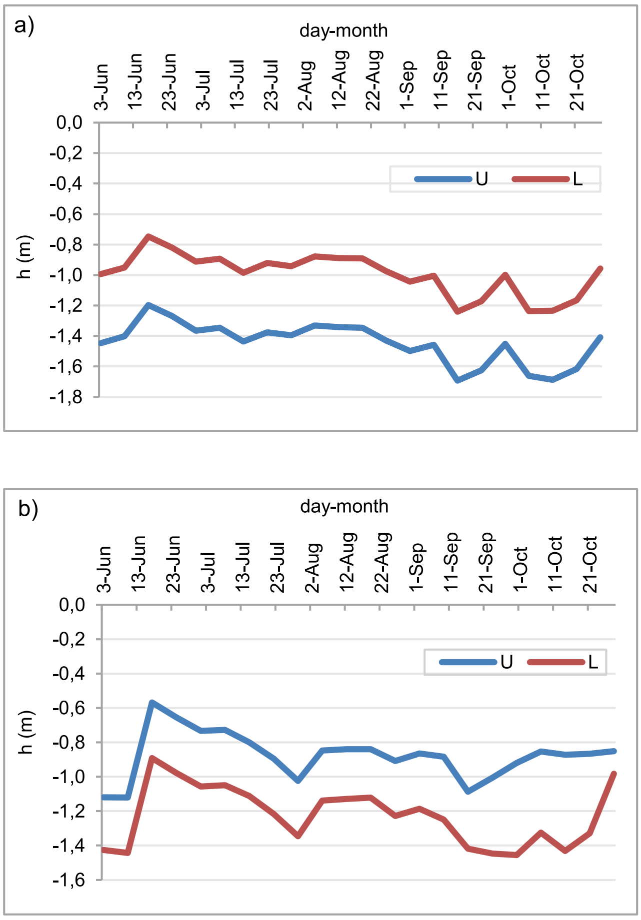

Fig. 5. The upper (U) and lower (L) water levels at the damming structures in the period of June–September 2019: a) BP 6, b) BP 35; source: own study

HYDROLOGICAL MONITORING

Hydrological monitoring was conducted at the Czarny Rów water course, which is main a source of water for irrigation, and melioration ditches as well as were measured ground water levels between ditches. Measurements of water flow rates were conducted at water intakes supplying the melioration ditches and at water outflow, too. As part of weekly field tests and measurement sessions, water flow rates were performed in several hydrometric sections at the Czarny Rów course and in melioration ditches using an electromagnetic flow rate meter with datalogger (Sensa Z 300, OTT Hydrometrie). Both water level measurements focused on upper and lower water levels at dam structures, and groundwater levels were done automatically using Solinst Levelogger submersible pressure sensors at 10 minute intervals. These data gathered in the recorded memory were downloaded once a week. For the purpose of atmospheric pressure compensation, a sensor installed in the well adjacent to the object was used.These automatic measurements were suplemented by manual measurements in additional points.

All hydrological monitoring measurement data were collected in the database and used to evaluate subsequent versions of the simulation model of operational irrigation and drainage planning. An example of changes in the water levels: upper (U) and lower water (L), at damming structures BP6 and BP35 is shown in Figure 5. The changes in groundwater levels at research locations Czarny Rów no. 2 (CzR22_2) and Czarny Rów no. 3 (CzR22_3) are shown in Figure 6.

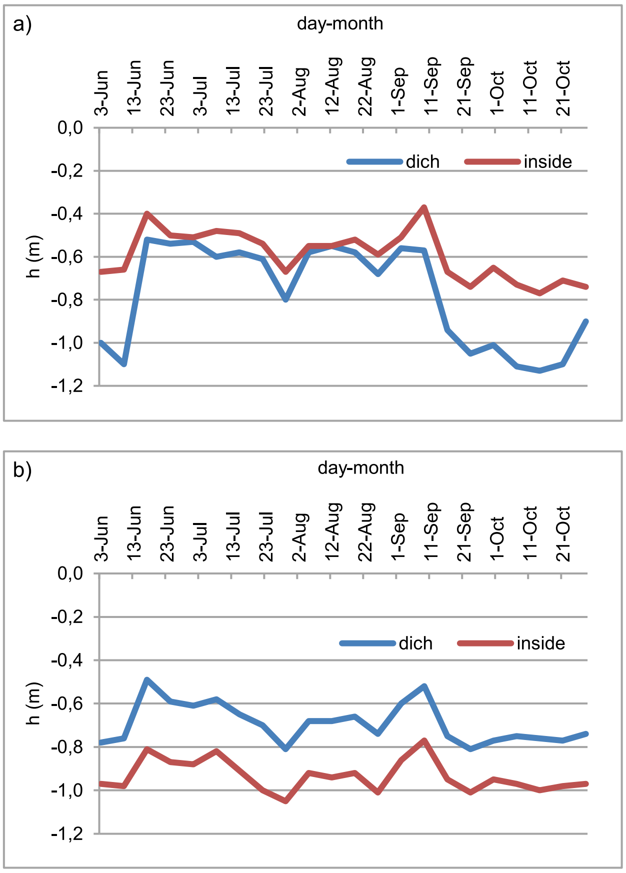

Fig. 6. Groundwater levels below ground surface at the research locations Czarny Rów – B1 in the period of June–September 2019: a) no. 2 and b) no. 3; source: own study

CONCLUSIONS

The AgHMM system in the INOMEL project is defined as a system of ground-based and remote sensing measurements, assessments and predictions of agro-hydro-meteorological characteristics of individual melioration systems, data collection and transmission, processing, and communication e.g. farmers, water management companies, and farming advisers. During the research phase of the project, the monitoring system realized the following goals:

– monitoring of changes occurring in the atmosphere, pedosphere, and hydrosphere at each of the tested melioration systems;
– regular transfer of measurement data and short-term forecasts of hydro-meteorological conditions, and their use as input data for the melioration system-level operational planning models.

The data collected by AgHMM system are the input for software which supports irrigation/drainage decisions. On the basis of current monitoring data and forecasts, system of operational planning of regulated drainage and subirrigation indicate the need to input or discharge of certain amount of water from the melioration object. Conducting water management in accordance with the software indications allows to maintain the ground water level ensuring optimal water supply to plants.

The author of the study believe that the AgHMM system will contribute to an appropriate agricultural water management and optimalization of the available water resources and to reduce the negative effects of harmful weather events. Thanks to activities such as irrigation and drainage it could to contribute to maintaining a soil moisture level optimum for plant growth. Such actions in relation to the Czarny Rów B1 object, described in detail in the paper, are intended to provide farmers with a high and stable hay yield at permanent grasslands.

During the operation of the AgHMM system at Czarny Rów B1 site, it was found that the applied soil moisture measurement system using profile probes and soil moisture sensors gives overestimated values of VWC in relation to the measurements made with instruments using the TDR method. An uncritical approach to the obtained data could cause significant errors in the output of the operational planning model. This fact made it necessary to perform additional soil samplings and to verify the value of soil moisture using the dryer-weight method.

The measurement's part of meteorological monitoring was smooth, while there were the problems related to the quality of some precipitation forecasts. A preliminary assessment of their reliability, especially for days with precipitation, showed that the values of the forecasted daily precipitation totals were often significantly different from the real ones. In the case of forecasting days without precipitation, these forecasts were more reliable. Thus, the opinion formulated by various authors and supported by the authors' experience that this weather parameter is difficult to forecast was confirmed. This happens especially in the warm season, when the possibility of precipitation formation depends on the development of the convection process in the incoming air mass. These in turn depend on the influence of local factors, such as land cover, topography, location of water reservoirs etc. Systematic observations of precipitation in the research areas during the INOMEL project in the very dry growing seasons 2019–2020 confirmed their significant variations.

Long-term hydrological drought occurring in both years caused a significant lowering of the water table and difficulties in measuring flow rates at the main water course and in the melioration ditches. Many times water flow rate dropped below the minimum values registered by the electromagnetic flow rate meter. Another difficulty was the unexpectedly mowing of the plants growing in the main water course and the neighbouring melioration ditches. During these periods the water management company administering the melioration object had to lower the water table, which also affected our ability to perform water flow rate measurements. On the other hand, there were no problems with the operating water table level measurement system in the Czarny Rów in water course and in the ditches as well as ground water levels.

To summarise it can be assumed that the AgHMM system has been correctly designed and deployed, and fulfilled goals assumed for the INOMEL project. The experiences gained during the preparation and system operation will be used in deploying it for commercial purposes and in the next research projects.

ACKNOWLEDGMENTS

This study was done within the project "Technological innovations and system of monitoring, forecasting and planning of irrigation and drainage for precise water management on the scale of drainage/irrigation system (INOMEL)" under the BIOSTRATEG3 program, funded by the Polish National Centre for Research and Development (Contract no. BIOSTRATEG3/347837/11/NCBR/2017).

FUNDING

This research was funded by Polish National Centre for Research and Development (grant number. BIOSTRATEG3/347837/11/NCBR/2017).

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