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The influence of hydro-climatological balances and Nature-based solutions (NBS) in the management of water resources

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ABSTRACT. This article offers a historical review of (cognitive) scientific research that demonstrates the development of key concepts relating to balances in the hydrological and hydro-climatic cycles, thereby supplying a basis for quantitative and qualitative assessment of renewable water resources. The review reveals the direction knowledge took as it developed through successive cognitive and applied stages. The emphases are on how global and regional hydrological conditioning underpin integrated concepts for the management of water resources. The primary aim of this article is to describe the main achievements, approaches and scientific initiatives, along with their theoretical underpinnings, in the hope of encouraging application and further appreciation. Attention is thus paid to milestones along the road to global development, as manifested in the (at times abruptly changing) effort to better assess and understand the use of water resources in various economic, social and ecological activities. The aim is first and foremost to encourage the achievement of sustainable development as humankind's main hope for the future. A further focus is on initiatives, scientific issues, and concepts that have been espoused by international organisations and illustrate the increasingly essential harmonious use of water resources at local, regional, continental, and planetary scales. Relevant global conferences have demonstrated wide readiness to adopt declarations, or to issue appeals and resolutions, in support of fuller assessment of renewable water resources. Examples of excessive use have been identified, and efforts have been made to counteract both floods and deficits, and hence avoid crises. These deliberations have also stimulated long-term forecasting, for periods up to 2030 or even 2050. Also stressed here are the challenges, inspirations, and achievements of pure and applied science when it comes assessing the risk that the Earth's potential to supply water resources will be exceeded. The suitability of current assessments of water resources is evaluated, and reference made to ecologically-integrated answers such as Nature-based solutions (NBS), as backed by the UN and UNESCO (2018) in combination with principles set out in the EU's Water Framework Directive (2000/60/EC).

KEYWORDS: renewable water resources, hydrological-climatological water balances, approaches, concepts, Nature-based solutions (NBS).

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1. FOREWORD

The water in various forms that is an essential component of the geosphere is also a basis for the existence of our planet's living world or biosphere. Although water is a renewable natural resource, its quantity is such that the matter and energy associated with its presence in the epi-geosphere are limited. Key features include ubiquitous presence and uses in various sectors of the economy. The consequence is that water is a common economic good of great importance. Nevertheless, water resources are more limited by the overriding impacts of demographic, economic, climatic, and other anthropogenic factors than they are by natural renewability.

The main subject of interest here is the renewability of terrestrial water resources, i.e. the entirety of actually or potentially available water of suitable quantity and quality to meet defined demands (*Międzynarodowy Słownik Hydrologiczny* 2001).

This article seeks to achieve a synthetic, historically-based conceptualisation of the science of water resources, through which increasingly complex and technologically advanced methods can inspire more effective assessment and use of water. From the outset, integration of theory and practice has been a key pragmatic element bringing water management closer to more favourable solutions for utilisation, planning, and management.

The background to this article's content and objectives is provided by the natural shaping of the water cycle and its components in the environment, as the basis for quantitative and qualitative environmental aspects and the regularities underpinning spatial and temporal changes.

IDEAS FROM SCIENCE AND PRINCIPAL CONCEPTS OF THE HYDROLOGICAL CYCLE

Natural water circulation can be quantified in the form of the water balance that represents a basis for the management of water resources in an area and is also of fundamental significance to nature conservation. A basis for the water-balance equation is to be found in "the law or principle of mass conservation" as formulated by Einstein (1879-1955) – the very famous German physicist, creator of the general and special theories of relativity, and the person who emphasised the constancy of mass and energy, with the two nevertheless being interconvertible. This kind of thinking may ultimately trace back to 15th century descriptive formulations arrived at by Leonardo da Vinci, not least in the matter of the water cycle within a drainage basin (Richter 1956). Biswas (1970) considered that da Vinci's work had led Newton (1643-1727) to his laws relating to the conservation of matter and energy, as well as gravitation. Circulation of water in nature as described by da Vinci makes visually clear the causes and consequences of many component processes that can be confirmed by simple measurement, attesting therefore to far-reaching scientific intuition about the interdependence of phenomena and factors. Premises supporting these concepts relate to spatial and temporal continuity and an unchanging quantity of water circulating in nature.

Craig et al. (2001) followed earlier hydrologists and geophysicists in maintaining that the amount of water globally remained constant, whereas this idea was not confirmed in research from the first decade of the 21st century, not least from American astrophysicist Lewis (2012).

Documenting the further growth of knowledge about water, Biswas (1965, 1970) mentions Pallissy, active around 1550 in France and the developer of ideas about the origins of precipitation in a river system, as well as springs and underground waters. These concepts then offered the basis for assessment of renewable resources, as indeed Galileo, Descartes, and Gastelle (17th century) all proceeded to do.

Cognitive understanding of the hydrological cycle proceeded in stages. The American geophysicist Newton in his *Encyclopedia of Water* (2003) states that increased understanding reflected advances in measurement techniques, calculation methods, and scientific concepts, as accelerated by quantitative hydrology and mathematical modelling in the service of economic forecasts. The development of water balances was thus dependent on the length of measurement series and the scale of the analysed object (for example, a drainage basin or a floodplain).

According to Biswas (1965, 1970, 1978), true development of scientific hydrology took place in the 17th century, with the first more-precise methods of measuring flows then representing a milestone in the development of quantitative resource assessment.

It was the second half of the 17th century that brought the beginning of continental hydrology, much later termed global hydrology by Kalinin. Bierkens (2015) presented the contemporary state, trends, directions, and directives underpinning the development of knowledge about water resources.

Theoretical foundations for the assessment of water resources in scientific publications first gained support from real measurements from such large international rivers in Europe as the Elbe, Rhine, and Oder. Measurements began to cover a broader scale from the end of the 18th century onwards, as intensive engineering work to regulate rivers was undertaken (see Biswas 1962, 1970 after: Maass 1870).

Representatives of the American engineering school associated with Stanford University in California, above all Linsley and Franzini (1972), devised strong theoretical foundations for the calculation of flowing water resources, as well as the behaviour of rivers at times of high-water events and flooding. From this point on, there was a broader movement seeking to put in place a rational model of calculating flows at times of flooding. The model was based on engineering studies involving 24-hour maximum precipitation and including factors such as evaporation, infiltration, and runoff via streams. Morley (1855), who was the biographer of Pallissy, thus dealt with a reconciling of theory and practice.

A key breakthrough in hydrology and its practical form (water engineering) was a modern handbook by Chow (1964) entitled the *Handbook of Applied Hydrology*. Even today it may not be described as outdated. In turn, those following the development of hydrology and water management in the USA should not ignore the modern Polish handbook from Lambor (1965), which offers a cohesive presentation of the relevant fundamentals, assessment methodologies, and management principles, as supported by numerous examples of problems and solutions arrived at on various continents and in many different regions.

2. INTERNATIONAL DIALOGUE AND PROGRAMMES CONNECTED WITH WATER RESOURCES AND MANAGEMENT

International interest in water, and particularly the resource and its quantity, use, management, and protection, arose in the mid-1970s and has continued to the present day under the auspices of the Geneva-based World Meteorological Organization (WMO). In the interests of forecasting and the methods of practical hydrology, the WMO issued a Fifth Edition (1994) of its guide for evaluating water resources. The role of the United Nations (UN) has become stronger as it strives more and more determinedly in the direction of joint international action, irrespective of whatever geopolitical blocs may be in place. It was on the initiative of that organisation that a first UN Conference on Water was convened at Mar del Plata (Argentina) in 1977. The main objective was an assessment of the status of water resources and a desire to assure all human beings access to water in appropriate quantity and of appropriate quality. Attention was paid to the socio-economic need for the water present on the planet, with further requirements that efficiency of use be increased, along with states' readiness to act in the face of a looming global water crisis, at the time considered likely to make itself felt before the end of the 20th century.

A summary of established international political dialogue in the last 25 years of the 20th century was produced for the Mar del Plata Conference by Biswas (2004). Key emphasis was then placed on global change in the Earth's water resources. The need for something to be agreed upon and established was widely recognised and emphasised, given what had been anticipated for the First Climate Summit (Conference of the Parties to the UNFCCC) held in Kyoto (2018 brought the most recent COP, COP 24, in Katowice). Rahaman and Varis (2005) published a key article on the state of management of water resources, with much emphasis placed on evolution, prospects, and future challenges, and stressed the need for integrated water management, which accounts for economic, social, and environmental/ecological aspects, as well as regional specifics.

Interlinkages between the systems of thought globally represent an issue of overriding importance supported by the UN, not least via its High-Level Panel on Threats, Challenges and Change. We also need to recall the precursors from Scandinavia who had significant input into the development of the sustainable development concept, including the future role to be played by water. Those in question were the then (1977) Prime Minister of Norway, Gro Harlem Brundtland, as well as Malin Falkenmark of the Swedish Academy of Sciences (in 1987). They regarded as crucial a holistic approach to meeting social, cultural, economic, and environmental needs where the uses of water and the environment were concerned. The World Commission on Environment and Development's *Our Common Future* report (1987) refers to climate change and its consequences for desertification, forest degradation and felling, water shortages, and the threat to biodiversity at the levels of the species, the biome and the phytocoenosis, most especially wetlands, which are dependent on sources of water. This report was a key stimulus for further ground-breaking action in the name of what became known as sustainable development goals.

Falkenmark (1983, 1984, 1987, and 1991), and other international studies justified the protection of water resources in line with the growing risk or probability of the Earth's potential being compromised by the excessive use of water. She also, individually (1987, 1989/1990), and together with da Cunha (1989/1990) and others (1991), sought to justify strategies for the future development of the Earth that entailed an awareness of the protection and saving of water in planning and in other kinds of decisions such that the management of water might be optimised in the context of scale, factors, and preferences. Economic, social, and ecological aspects were propounded as being of the greatest importance.

Reports seeking to raise levels of knowledge and awareness of the sustainability of developments in water management include work brought out consecutively by the Intergovernmental Panel on Climate Change (IPCC 2007, 2012, 2013, 2014). Furthermore, relevant key events on the world scale included the "Earth Summit" convened in Rio de Janeiro in 1992, the *Agenda 21* document associated with it, and the UN's Millennium Declaration and Development Goals, the last in force since 2015 and still binding.

It is also worth citing the article by Montanari et al. (2013), in which members of the International Association of Hydrological Sciences (IAHS) describe foreseeable changes that pose a threat to water resources globally. Subsequently, McMillan et al. (2016) maintained the IAHS stance, but emphasised global hydrological prospects, some looking very unfavourable because of the likelihood of increasing water shortages and desertification.

Rockström and Falkenmark (2014) also noted the development of methodology relating to resistance and economising on resources in the interests of human existence, with proposals of the kind referred to in Table 4.

Many recent studies deal with water resources as they relate to environmental limitations, farming systems, and human food security (Rahaman, Varis 2005; Springmann et al. 2018), while Kindler (2018) and Varis et al. (2017) address the matter of worldwide use of water by reference to just a few dimensions of the protection of those resources essential to the production of food items (not least those to be imported or exported).

The end of the 21st century's first decade brought many new actions focusing on the relationship between ecology, the reshaping of water resources under the influence of global warming, and the capacity of water balances and the hydrological cycle to go on supplying water. Attention is given to ecological processes that affect water quality and quantity, limitations on evapotranspiration, and the barriers to the consumption of water resources in extreme circumstances involving droughts or flooding.

Rockström et al. (2014) – responding to Vörösmarty et al. (2010, 2013) – claim that a future bridge between ecohydrology and uncontrolled resistance on the part of the environment may give rise to dramatic Anthropocene phenomena and processes that will disrupt the sustainability of water resources worldwide.

Today the preference is for closed-cycle water management. This approach is economical with water resources and involves links in the chain that comprises abstraction from the environment, use, and discharge. Where there is considerable access to limited resources, synergies involving demographic processes (population increase), or a larger number of people placing a burden on the management of renewable resources, then renewability becomes limited and there is a lack of equilibrium that works to minimise values for resource use.

Influential accords reached through the work of international organisations from the end of the 20th century through 2015 include those under the auspices of the UN, FAO ICSU, and the World Bank. The IGBP, IHD IAHS, IUNEP, and IWRM Programmes are involved, along with consensus texts from or relating to the ESSP and EEA, *Future Earth*, IHP UNESCO, the Club of Rome, the "Water for Life" decade, the Pope's 2015 Encyclical entitled *Laudato Si*, and NGOs including such church-related examples as *Listen to the cry of the Earth and the cry of the poor*, as well as the *Global Catholic Climate Movement*.

The key issues for these accords address awareness of the use and consumption of water resources and special protection for areas of deficit or accumulation within cities. In each case excessive outflow is to be prevented, sustainability encouraged, amounts of wastewater reduced, and appropriate priorities determined. Drought represents a major challenge for agriculture, horticulture, livestock-raising, and forestry.

The distinguishing of the different types of water resources and their precise definitions (for example as green or grey water) reflects the way that water may be subject to various processes before it, for example, becomes effluent. It is possible to steer such resources, and engage in appropriate management or allocation of them.

Anticipated droughts and periods of low levels of surface water or groundwater as a reflection of global warming and excessive use have been worked on by Tallaksen and Van Lanen (2004). In turn, Veldkamp et al. (2015) draw attention to significant changes (and underlying mechanisms) in global shortages of water during the year, with implications for socio-economic changes in agriculture and recreation. Moreover, Van Beek et al. (2011) reveal that even global monthly changes affecting meteorological events may tend to stress plants and limit access to water retained in the soil, which is needed if high yields are to be obtained. A recent report from Poljanšek et al. (2017) summing up knowledge on disaster risk management resorted to the perverse title "better to see it than to lose it".

In sum, such extensive, multi-dimensional development of knowledge of quantitative assessment in water-cycle management and balancing must include mathematical modelling (deterministic, stochastic, or conceptual). Beyond hydrology, environmental, and ecological factors, models will need to address economic and demographic development scenarios. The ultimate aim in each case is to make projections possible, with verification by way of measurement and monitoring, thereby supplying a basis for the forecasting of changes in the resource under the influence of various global and anthropogenic activities.

3. THE DEVELOPMENT OF WATER-BALANCE PROBLEMS AND CHALLENGES

As the content of previous sections makes clear, the cognitive development of the hydrological cycle was a very protracted, step-by-step process extending from the 16th through the 19th centuries. It centred on a developing understanding of genesis and interdependence, and the uncovering of empirical premises confirming variability across both space and time. As Biswas (1965, 1970) shows, and Dooge (1959, 1974) confirms, opportunities arose for further qualitative and applied development, with quantitative indicators characterising a studied basin better and better integrated. An outline of the scientific thinking behind better acquaintanceship with the water cycle was imperative, with mathematical descriptions of the processes, given the need for real-life solutions, practical applications, and full insight into the renewability of water resources, the way they originate, and the way in which changes can be evaluated.

Recent centuries brought major developments to deriving hydrological balances for drainage basins. As Biswas (1978) notes, the concept of the hydrological cycle developed in France by Delamétherie (1743-1817) – albeit on the basis of ideas da Vinci outlined – was the first approach seeking to account for an arithmetic regularity by way of mathematical description. It was then up to a water engineer from Leeds (UK) – Smeaton (1724-1792) – to engage in the measurement of flow, although he did not conceive an algebraic equation by reference to the French findings.

The use of mass (or volume) balance as a means of both assessing and studying renewable water resources on the basis of mathematical description of the hydrological cycle has been employed since the end of the 19th century. The form and application have remained the same through all this time, notwithstanding developments and a process of ongoing modification. The balance structure has always been based on the same assumption: that incoming amounts of water are equal to those passing out of a given area over a given time. However, choices then need to be made in line with the objective that is to be served. The mass balance, as the simplest of the mathematical models, may first need recalling here, even if it is probably well known.

Arising out of the laws of conservation of mass and energy, the water balance equation remains a numerical representation of the hydrological cycle characterising a drainage basin, and is still useful, albeit often now in forms that reflect ever-greater expansion, and methodological perfection. In classical hydrology, the terms used for the components of the water balance are used interchangeably with those applied to components or elements of the hydrological cycle. The balance for the catchment or basin of flowing waters, lakes, swamps or aquifers, including different components of the water cycle in the area under consideration, remains in close linkage with, and is very much conditioned by, various renewable sources of water, which are integrated by the processes of water cycling, whether on the surface, just below the surface, or deeper underground.

The development of hydrological balances proceeded in stages. The water cycle required dynamic and quantitative conceptualisation representing a basis for the management of water resources on different scales. It was accepted that this should be termed the water balance, and be time-related. The German geographer Keller (1980) followed Soviet hydrologist Lvovich (1969, 1974) and Mikulski (2006) in ascribing the form of the quantitative raw balance to Brückner (1862-1927), a German geographer-climatologist. The precise date and form of the equation for this raw balance of resources are not known, but can be hypothesised (after Mikulski 1998) as a 1904 innovation. The first form of the equation was simple, with atmospheric precipitation (N) = river outflow (A) + water loss (W), this being written using the original nomenclature in German as:

$$\begin{gathered} N = A + W \\ \textit{Niederschlag} = \textit{Abflus} + \textit{Wasserverlust} \end{gathered} \tag{1}$$

Keller (1980) considered that the equation initially served (for example German geographer and geomorphologist Penck in 1896) in determining the flow in a river from a known precipitation total, in the case of an inadequate supply of measurement data. Rather earlier it had emerged, as an 1883 achievement of Polish water engineer Iszkowski (Mikulski 1998), that field evaporation might also be calculated as in Equation 1 from the difference between precipitation and river outflow ($W – E$, where E is evaporation). The year 2008 also marked the 135th anniversary of the publication of Iszkowski's work, which used Penck's equation in its calculations, and went by a title approximately translating into English as *On evaporation in the field*. It was obviously concerned with the water cycle on planet Earth, but did not take account of the evapotranspiration process. It can be presumed that Penck and Iszkowski were well acquainted, thanks to contacts in Vienna and Lvov (at that time in the Austrian province of Galicja).

Penck's 1896 equation proved useful to the aforementioned Brückner (1904), and then to Russian hydro-engineer in the Don Basin Oppokov (1905), as they tried to account for differences in drainage-basin water balances over the long term, as compared with mean values (Mikulski 1998). To this end, an initial improvement involved a term for change in the level of retention (ΔR). An equation modified in this way has persisted to the present day.

The water balance thus came to be founded upon the assumption that, in a period Δt,

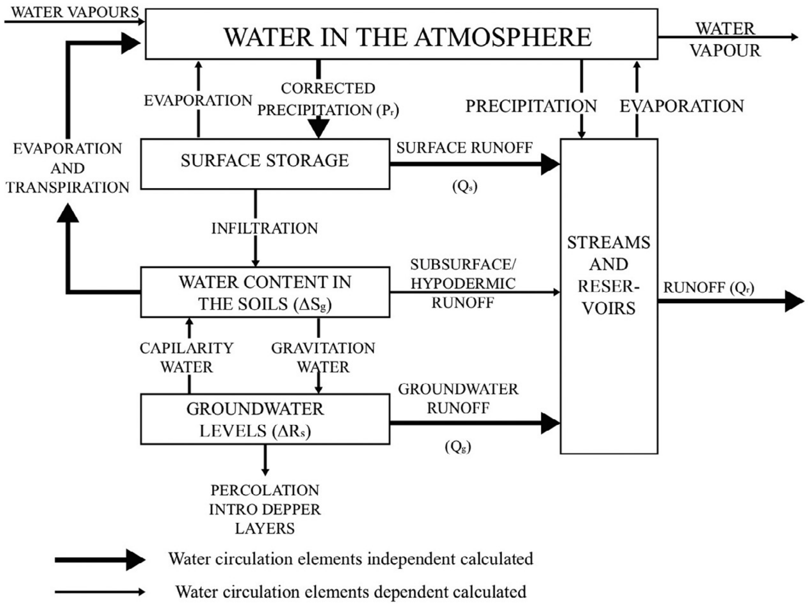

Fig. 1. Classical scheme for water circulation in the catchment (based on Soczyńska et al. 2003)

the total amount of water entering a given hydrological unit (drainage basin) is equal to the sum of losses plus any change (in comparison with the original) in the state of final retention. However, retention as a separate component was identified in the balance equation only thanks to Oppokov as the fraction of precipitation that reached the drainage basin, but neither flowed out nor evaporated, at least over the period under consideration.

A breakthrough in the assessment of drainage-basin processes and the development of water balances involved dividing the discharge hydrograph into surface and underground phases; as well as the method for assessing evapotranspiration. Application of mathematics, information technology, and the theory of systems in the 1970s and 1980s resulted in the development and use of systems-theory computer techniques. These developments supported the rapid, revolutionary development of mathematical modelling based on Bertallanfy's theories in describing the transformation of ever-larger empirical data sets (Haimes 1987; Soczyńska 1995). It became possible to apply an ever-greater number of generations of models, with the balance equation becoming the classical approach, alongside new ones, for example those involving graph theory, fuzzy sets, etc. Statistical and stochastic models (and among them dynamic water balances like CLIRU N-3) have contributed to the assessment of water resources on the basis of climatic or hydrological plus climatic data (Kaczmarek 1996) integrated with variables characterising atmospheric or soil, vegetation-related, and riparian processes.

Rates of loss or gain of water resources may vary under various anthropogenic pressures, and may head in opposite directions.

Where the balance period is markedly shorter, there is a need to take account of dynamics of water and heat in a basin that can be safely ignored when the period is an annual one. The equation for the water balance then (after UNESCO 1971 and Lvovich 1974)[1] is:

$$P + R_1 = H + E + R_2 \qquad (2)$$

where: P is precipitation; R_1 represents initial level of retention; H is outflow; E – evaporation; and R_2 – level of final retention.

This equation assumed the full form of the developed balance (Kędziora 1995), in line with:

$$P_r + E + S_p + S_g + S_a + \Delta R_s + \Delta R_p + \Delta R_i = 0 \qquad (3)$$

where: P_r represents precipitation in all its forms, E is evapotranspiration (field evaporation); S_p surface runoff; S_g groundwater outflow; S_a apotamic flow (percolation), ΔR_s the change in ground retention, ΔR_p the change in surface retention (in rivers, lakes, or wetlands), and ΔR_i the change in retention due to interception by plant cover (Fig. 1).

If water resources in a given precisely-defined area (basin) gain expression through a time function with a freely-selected time-step, then, as developed by Overmann (Soczyńska 1997) and Owens and Watson (1979), we arrive at the following 19-component version:

$$\begin{gathered}(P_1 + P_2 + P_3 + P_4) = \\ (H_p + H_f + H_{gd} + H_g - H_{ap}) + \\ (E_w + E_p + E_t + E_i + E_c) + \\ (\Delta R_p + \Delta R_a + \Delta R_f + \Delta R_g + \Delta R_{ap})_{/\Delta t}\end{gathered} \qquad (4)$$

where: P_1 constitutes precipitation measured 1 m above the ground; P_2 is the further amount of precipitation arising out of systematic measurement errors; P_3 is "horizontal" precipitation (involving rime or hoar frost and fog); P_4 is precipitation originating with the condensation of water vapour in the air as dew; H_p is the surface outflow or runoff; H_f the sub-surface flow out of the zone of fluctuation in levels of groundwater; H_{gd} the inflow of groundwater into the basin; H_g underground outflow into watercourses; H_{ap} underground apotamic outflow into deeper rock layers; E_w evaporation from open water surfaces; E_p evaporation from soil, snow, ice or impermeable surfaces; E_t transpiration by plants; E_i losses due to interception by plant cover; E_c losses reflecting chemical transformations; ΔR_p changes in surface retention; ΔR_a changes in the aeration zone; ΔR_f changes in retention in the saturation zone relating to a variable water table. Then ΔR_g represents changes in retention of potamic groundwater (percolation); ΔR_{ap} changes in retention in the saturation zone of fluctuations of deep-lying groundwaters not associated with river drainage, and Δt the time step for the calculations.

As can be seen, the development of such an equation requires the collection of a great deal of measurement data. Should that be lacking, we resort to empirical formulae allowing for direct or indirect estimation of some of the 19 elements of the cycling of water (or processes) considered to be operating in a basin. Sometimes consideration is confined to the more important factors, sometimes even to just one of them (Fig. 1).

As has been noted already, the dynamic hydrological balance in a natural basin can be expressed with a set of five subsystems, or even a greater number (Fig. 1), that are interlinked in the manner depicted in Equation 2. Conservation of mass and energy dictates that transformation of any component

[1] The geographical and hydrological method developed by Lvovich was dubbed his favourite son by colleagues. It was a six-element system for a balance equation (after Mikulski 2006).

of the balance on either side of the equation influences the remaining components.

The dynamic balance for a natural drainage basin can have anthropogenic (water management-related) components incorporated into it, in relation to both incoming and outgoing resources. Quantitative and qualitative changes characterising the cycling of water and brought about by anthropogenic factors may arise throughout a basin, or in just a part thereof. Indeed, change may be confined to the channel of a single watercourse. Likewise, the impact involved may be episodic, short-lived, periodic, seasonal, annual, or multiannual, and is determined by physico-geographical (including climatic) conditions, compounded by the effects of various forms of economic management that modify retention, outflow, and evapotranspiration, or a connected basin. These factors are most often multi-directional and very difficult to assess objectively, especially because of the lack of a frame of reference, or initial, natural background conditions. It should be stressed that the directions of impact of anthropogenic changes may vary, and may sometimes be synergistic.

The compilation, in an independent or dependent manner, of all component elements of the balance described by the relevant equation should also be accompanied by a calculated error of estimation.

The equation balance remainder should be distributed between all components proportionally to their significance (Ozga-Zielińska, Brzeziński 1994). However, subsequent research has shown that these errors should not be distributed among all elements of the equation but expressed in an additional element, the so-called non-classed water balance (η):

$$P_r - E_t - (H_p + H_p) \pm \Delta R - \eta = 0 \qquad (5)$$

UNESCO has recommended a version from Sokolov and Chapman (1971, 1974) after Sugavara, in which water-balance components must be evaluated in relation to their variability. The evaluation error of each balance element should then depend on the distribution and variance, measuring instrument accuracy and measurement frequency, subordinated to systematic and random errors.

The drainage dynamic water balance equation as written by Overmann (Soczyńska 1997 et al.) took the form:

$$P_r(t) = H_{p(t)} + H_{g(t)} + E_{(t)} + R_{(t)}/\Delta t \qquad (6)$$

In such a complex, multi-element form, the water-balance equation is very difficult, if not impossible, to resolve for a small-scale cycle, with the result being duplication (double counting) of circulation caused by the protracted or short-lived presence of water by way of retention.

4. PROBLEMS AND CHALLENGES SURROUNDING THE HYDRO-CLIMATOLOGICAL BALANCE

The atmospheric nexus with the cycling of water is of particular importance, if hard to estimate. Measurement and calculation methods associated with it are very complex and have tended to accumulate ever more parameters as time has passed. The devising of balances for elements of the climate may resemble or be identical to those relating to the hydrological aspects, or else proceed with a different rhythm. Three links involving the exchange of matter and energy have been described in theoretical terms, i.e. the atmospheric (*A*), the surface-related (*S*) and the soil/ground/plant-related (*P*, *G*). There are naturally interactions in play between all of these (Fig. 2).

Each of the evaporation processes (or types related to cover), e.g., field evaporation, evapotranspiration, guttation (interception by plant cover), requires a separate physical and mathematical approach (Monteith 1981; Kędziora 1995; Kowalik 1995, 2010; Jaworski 2004; Gutry-Korycka 2007). Three important ways of doing that are worthy of mention: (1) diffusion, as described by British physicist John Dalton in 1802 (as referred to in Biswas 1978; Szymkiewicz, Gąsiorowski 2010); (2) the balance of heat energy encapsulated in equations developed by American astrophysicist I.S. Bowen in 1926 (Kędziora 1995); and (3) a concept relating to heat flux from Bowen, as well as Australian physicists Priestley and Taylor (1972), and British experts on evaporation and evapotranspiration Penman (1956) and Monteith (1981, 1985).

The greatest number of creative theoretical and empirical solutions were arrived at by agro-hydrologists of the Dutch school (de Wit 1958, 1965; Bierhizen, Slatyer 1965; Ritema 1969; Ross 1970; Ritema, Endrödi 1970; Feddes et al. 1980), whose work included the roughness of cultivated plants, increments in biomass, transpiration, interception, and various types of evaporation. Issues of gaseous exchange revolve around photosynthesis, as well as the exchange of greenhouse gases, with

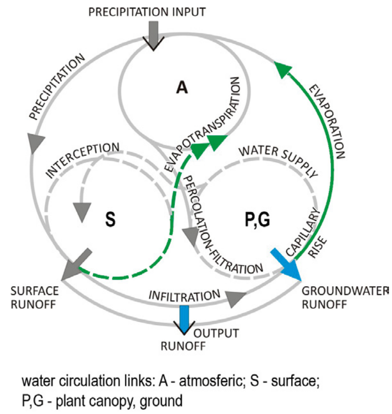

Fig. 2. Water circulation links showing locations of blue, gray, green water (based on Kędziora 1995, modified by author)

much work undertaken by British workers, as well as Scandinavians (e.g., at Uppsala and Århus).

Meteorological parameters in the near-ground atmosphere such as solar radiation (as the main source of energy), wind, air humidity, and the kind of vegetation covering soil all help determine the intensity of the process by which the gaseous exchange of water takes place. It has long been known that a particular role in the transfer of water to the atmosphere is played by vegetation cover and soil processes. The biosphere must thus receive a considerable amount of water (thanks to interception or dew formation), and of that only a small proportion is used in the development of biomass. The remainder of this water participates in overall transpiration from plant cover (Figs. 1, 2 and 3).

Water passing through the plant root system (rhizosphere) through osmosis and capillary action reaches the atmosphere via fine vessels, though arrival at the leaf may coincide with photosynthesis, with mineral substances taken from the soil combining with carbon dioxide (CO_2) from the atmosphere, with the participation of solar radiation, to build plant organic matter. It has been shown that the amount of water conducted by a plant is a function of these processes.

Regardless of the specific biome, the total mass of a plant is proportional to the amount of water used during its growth. This is an important feature of the hydrological cycle, which Falkenmark (1984) termed (from the point of view of water resources and their designation) "green water" (Fig. 3). Matricon (2000), Hoffman et al. (2000), Hoekstra (2003), Mioduszewski (2003, 2006), Chapagain and Hoekstra (2004) in turn revealed that the production of 1 kg in dry mass of grain requires ≈ 500 L of water, whereas the production of a 1 kg of cotton needs twice as much. These ideas can be generalized to other crops, as well

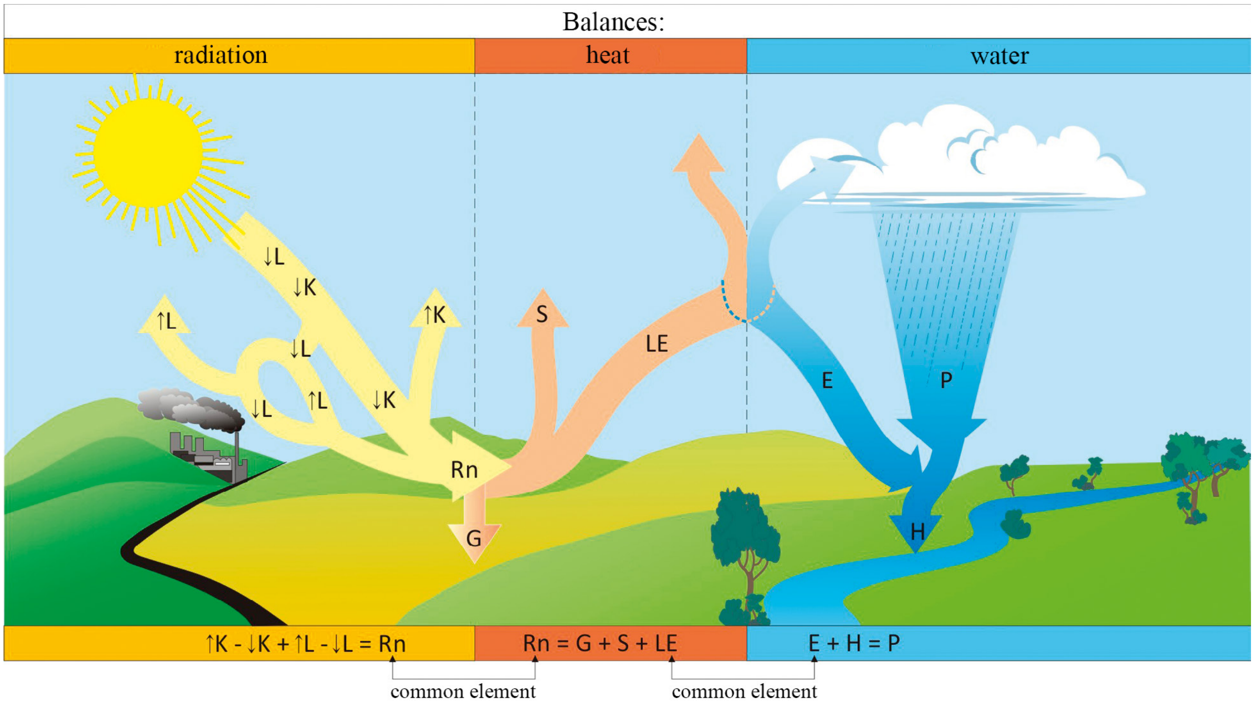

Fig. 3. Common elements of balances: heat, radiation, water balance (based on Kędziora 1995)

10

as goods for consumption or industrial uses; the concept dates to the start of the 21st century.

Evapotranspiration is a dual process: the effect of a phase-change resulting from evaporation at the land surface and from plant cover, and transpiration due to the activity of individual plants or plant communities. While precipitation is taking place, most authors ignore evaporation, though some may adopt a value for it as potential evaporation (E_p).

The simplest form of description nevertheless involves evaporation from the surface of a body of water, or from a solid object saturated in some permanent way. It is possible to mention two types of theoretical description of the process of evaporation. The first proceeds via transport with the aid of diffusion and the retention of mass (as theorised by Dalton in 1802). In the other, changes in the course of the process of evaporation are summarised as the amount used in the process of gaseous exchange, as change in water vapour per unit of time (Rodda 1953; Dobson 1977).

A method such as that involving heat balance allows for an estimation of the mean rate at which water is lost through the process of evaporation over a given time step. This method of approaching the issue gained dissemination very widely thanks to the school of American physicists founded in 1926 by Bowen and continued by many European authors, including the Briton Penman working in Australia (Penman 1956), as well as British physicists Thornthwaite and Mather (1957), Belgian agro-meteorologists van Bavel and Hillel (1976), British physicist Monteith (1985), Americans Gash and Shuttleworth (2007); and a well-known school of physicists and climatologists in the Soviet Union including Konstantinov (1963) and Budyko (1986).

In the approaches taken (and methods of calculation applied) up to now, appraisal of the processes determining levels of useable water resources include balances relating to radiation, to heat and to the active surface (i.e. the area of ground covered by vegetation, or else the open water surface). See Kędziora (1995) and Figure 3.

The common elements of the balance equations, with R_N being the residue in the radiation and heat balances expressed via equations 7a – 7d, are as follows:

$$\uparrow K - \downarrow K + \uparrow L - \downarrow L = R_N \quad \text{(radiation balance)} \tag{7a}$$

$$G + S + LE = R_N \quad \text{(radiation balance)} \tag{7b}$$

$$E + H = P \quad \text{(water balance)} \tag{7c}$$

$$R_N = G + S + LE \quad \text{(heat balance)} \tag{7d}$$

where: $\downarrow L$ is long-wave radiation reaching the land surface; $\uparrow L$ is long-wave radiation from the land surface; $\downarrow K$ is short-wave radiation reaching the land surface; $\uparrow K$ is short-wave radiation reflected off the land surface; S is the flux of sensible heat; LE the flux of latent heat; G is the flux of soil heat; E is the flux of water vapour; H is the overall runoff into a river; P is (real) atmospheric precipitation; and R_N is the differential balance for radiation.

The first controlling factor in the radiation balance is the albedo of the active surface, which varies through the year and during the growing season, since it depends on the physical type of land cover, including for example forest, exposed soil, open water, or snow cover.

The accumulation of snow in a basin and the intensity of melting are the most important factors determining the rate and magnitude of outflow due to melting, as it proved possible to establish both theoretically and empirically thanks to the work of such American geophysicists and engineers as Wilson (1941), the U.S. Army Corps of Engineers (*Snow Hydrology* 1956), and Grey and Prowse (1993). Polish scientists have made a major contribution to our understanding of how to describe phase transitions of water in terms of the physics of the processes involved (Dobrowolski 1923). The energetic balance for the modelling of thaw processes in line with streams of energy and the energy balance – as the algebraic sum of all the streams inputting to the surfaces of snow cover and departing from them, and as entered into approximate equations (7a-7d) was applied by Kupczyk (1980) and Soczyńska (1997).

English ecologists, Calder et al. (1992) and Halder (1992) used the equation described. Plant canopy transpiration (E) was estimated as the summation over a three-layer calculation with the Monteith-Penman formula according to Monteith (1965) applied at each level:

$$\lambda E = \frac{\Delta' H + \rho c_p \cdot \delta_q \cdot g_a}{\Delta + \left(\frac{c_p}{\lambda}\right)\left(1 + \frac{g_a}{g_c}\right)} \quad (8)$$

where: H = the available radiative energy for each layer of the forest; c_p = the specific heat of air at constant pressure; E = transpiration rate; g_a = canopy layer boundary conductance; g_c = canopy layer stomatal conductance; δ_q = specific humidity deficit; Δ' = rate of change of saturated specific humidity with temperature; λ = latent heat of vaporisation of water; ρ = density of air.

Following Landsberg (1986), radiation absorption by the forest canopy is approximated by the Beer-Lambert Law:

$$\ln\left(\frac{I_z}{I_o}\right) = -k \sum_{i=1}^{z} L_i \quad (9)$$

For example, for physiological studies in young *Eucalyptus* stands where: I_z = the radiation beneath increasing accumulation of leaf area; I_o = the net radiation above the canopy; k = an extinction coefficient (taken in this case as 0.5); L_i^* = leaf area index of layer i.

For each of the canopy layers, stomatal conductance, g_{si}, was calculated as:

$$g_{si} = L_i^*(g_{sui} + g_{sli}) \quad (10)$$

where: L_i^* is the leaf area index at given canopy layer; g_{sui} is the stomatal conductance of the upper leaf surface; g_{sli} is the stomatal conductance of the lower lead surface.

An interesting solution proving useful in spatial and water management and arising out of the heat and water balance is to be found in Schierbeek (1980). In a series of studies, example solutions were provided for water quantity and quality, soil-change technologies, and the planning and economic dimensions of land use, capped by mathematical modelling of processes and mechanisms that control the cycling of water in agricultural areas and depres-

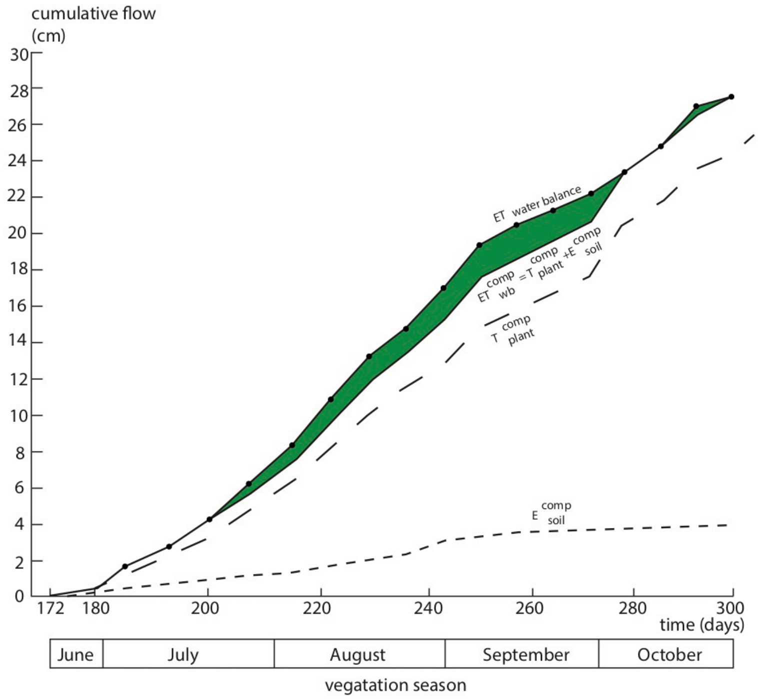

Fig. 4. Comparison of cumulative transpiration and soil evaporation as simulated with SWATR model with lisimetrically-measured data for a red cabbage crop growing on clay in the presence of a water table (based on Feddes et al. 1980)

sions. There is a high-level numerical description of infiltration into groundwater and aquifers. The modelling was partly achieved by using remote sensing for spatial identification of fields covered with various crops and the extents of different soils, in order to calculate net radiation (LE) as a function of evapotranspiration, and with the growth of crops simulated (Fig. 4).

As presented by Feddes et al. (1980), an example illustrates the water circulation system that Falkenmark (1988) termed "short branch," with wetting and alimentation of an agro-ecosystem on clay soil.

The magnitudes of actual water resources conceptualised either pointwise or spatially in the soil (aeration) zone are determined by reference to the water balance, which is the difference between incoming water (the precipitation total with an instrumental correction, P_r) and water lost through evapotranspiration (E_t), in a given place over a given period of time. This concept has been made clear empirically by such Polish climatologists as Łabędzki (2003), Wibig (2012), Wypych and Henek (2012), Kożuchowski (2014), Wibig (2017) and Wypych and Kowanetz (2017). They all deploy a rather different concept that determines a value for the water balance on an areal basis, with changes in retention ignored by means of longer-term averaging. In Polish, this is the *Klimatyczny Bilans Wodny*, i.e. the Climatic Water Balance (*CWB*), defined as the difference between the corrected mean total of atmospheric precipitation (P_r) and the mean total potential evapotranspiration (E_p), also termed indicative evapotranspiration, which is expressed as a water-column layer a given number of millimetres deep.

Evapotranspiration depends on the amount of accessible energy at the vegetated active surface. Quantitatively, this energy is the same as the solar radiation balance after Equation 7. Potential evapotranspiration may thus be denoted by one of several dozen formulae or empirical functions derived from one, two, or many meteorological parameters. Negative values assumed by the *CWB* indicate prevalent $E_p \geq P_r$ during the growing season, with a shortage of precipitation determining poor conditions for renewability of water resources. In long-term forecasting associated with agriculture's demands for water, *CWB* may be helpful in ensuring that greater harvests are obtained.

Other indicators of aridity of the atmosphere include a ratio of evapotranspiration to precipitation equated to a standardised empirical function corresponding to R_N as the product of the latent heat flux and precipitation. This indicator was proposed by Budyko (1977, 1986).

In summary, the water-balance equations presented in Sections 4 and 5, in their various forms, can be used in different approaches to the management of water resources, when incorporated into planning. Large amounts of data are required as well as adoption of different forms of the equation depending on the premises governing water use.

In relation to a type of economic planning, Lambor (1965), a well-known water-management specialist, drew a distinction between seven different categories of balance: the original or historical, the raw current (full or resource-related), the utilitarian, the planned, the prospective, the operative, and the dynamic. The choice then depends on the objective of the balance being estimated and the needs of water management itself.

The original or historical balance is related to the past, but still within either the Holocene or (if recognised) the Anthropocene. It entails the reconstruction of the cycling of water in the past, the aim being to research conditions in previous times, as well as trends associated with development.

The raw balance is a compilation of natural resources and losses within a defined area over a studied period of time, with no delving into uses and needs. Devising the balance involves reporting of incoming and outflowing water, as well as losses; with no account being taken of water use.

The natural or raw water balance may even take in all elements of the balance equation. If we confine ourselves to just two elements depicting water resources, i.e. precipitation and outflow, then what is being considered is a natural balance and a resource-based balance including field evaporation and retention.

The utilitarian balance presents, not so much the real state of water resources, as the state of use (reserves, consumption, and demand), with no account taken of changes in cycling and use, even though these factors may turn out to be necessary at a further stage of development. This balance is part of the wider static balance category.

The planned and prospective balance involves forecasting resource use and directing planned management in line with a development plan that takes account of an area's possibilities where resources are concerned. This is a dynamic conceptualisation.

The prospective balance, covering a period of 25-30 years, is at the same time a balance of the planned type.

The operative balance depicts the development of a planned balance as applied practically. It describes a dynamic configuration of incoming and outflowing water over time and within a given spatial unit.

The forms taken by the equations vary, as does the number of (independently) calculated elements.

Each form and each category relating to balances in the hydrological cycle may gain application in comparative or reconstructive studies (i.e. the recreation of the state of quasi-original water resources), or can serve in forecasting by way of a dynamic approach.

5. INCREASING CRISIS IN WATER RESOURCES – DROUGHTS

At the beginning of the 1980s, a dialogue and broad discussion commenced about the prospects for the development and protection of water, especially drinking water. Concrete actions began to be taken by such international organisations as the UN, WMO, IHD UNESCO, ICSU, WHO, FAO and many others (Section 3).

At that point, Sweden initiated a specific activity under the auspices of IHD UNESCO, ICSU, and IAHS, the newly-established IGBP and IGU, the WMO, etc., the main aim being to ensure the development of water management, to devise key directions and principles relevant to the use of renewable resources, and to identify barriers, factors, and restrictions. There is a justified need to apply methods from different disciplines, such as geochemistry, economics, biology, the social sciences, humanities, and ecology. The relationship between the rate of use of water and its quality must be considered, as well as the causes of limited-scope renewal surrounding changes in resources.

As her many studies show, Falkenmark (1983, 1984, 1989a-b; Falkenmark et al. 1991) played a pioneering role in formulating principles and devising ways of using surface and ground waters in relation to locations of intakes and with categorisation by precise criteria.

Thus far, the technical and ecological principles in force for intakes of water involve importing the water from source (underground) parts of a basin, with export taking place downstream. This dynamic has hydrodynamic and geochemical implications and is related to the way in which processes of self-treatment or self-purification operate. It is further qualified by water-use or water-consumption categories (Table 1).

This categorisation takes account of the objective of water use in relation to the form of human activity; it might entail types of economic sector, infrastructure, or environment, as Falkenmark et al. (1987) considered. The principal categories are related to types development, e.g., towns or cities, housing estates, villages, or industrial plants. A further category entails the irrigation of cultivated fields. Irrevocable losses have also been taken account of as a total (relating to forests, other areas used in agriculture, and pastures, and also in relation to whether these areas are subject to melioration, drainage, or irrigation).

Further pursuit of this kind of concept was facilitated by a debate organised in Stockholm on awareness of needs for water development, with primary barriers to its use identified, along with bases for renewable resources. The expectation was that measures would be introduced in relation to different groups in society, with different strategies pursued and different organisations working to resolve conflicts at different levels. Those involved ranged from the authorities to individual consumers, to high-level regional representatives, and these all gained representation in the multidimensional matrix devised by da Cunha (Table 2).

The objectives here are political or related to group preference, and also related to different emotional approaches to the matter of water shortage. Discussions centred around the devising of targeted activity to help understand the factors determining renewal in aquifers, as well as self-purification of waters subject to pollution, in order that water suitable for drinking may be obtained.

At the same time, attention has been paid to the regulations with which water-supply systems are managed, with account taken of decision-making about risks, needs and threats.

Castenson (1989/1990), Falkenmark (1989/1990) and Hoffman et al. (2000) sought to draw conclusions about how the consumption of drinking water should be prioritised in its var ous social, economic, and environmental aspects. Consideration was also given to the rate at which resources are consumed, and the influence of consumption on pollution and water quality. This is what da Cunha (1989/1990, page 27) did, by developing a suitable analytical matrix.

Awareness of the uses of water resources should respond to different levels of human activity engaged in at different levels of administrative organization.

Falkenmark and Chapman (1989) further presented (as in Fig. 5 here) a scheme relating to water needs with reference to the macro-perspectives of various countries. The intake of re-

Table 1. Principal categories of water use (based on Falkenmark et al. 1987; da Cunha 1989/1990)

on site		Location of water use		
		in stream	out stream (withdrawal)	
Economic sector	Agriculture, Forestry aquaculture	Rainfall in agriculture Forestry Swamp and wetland habitat Utilisation of estuaries	Fish and wildlife Utilisation of estuaries** Waste disposal	Livestock Irrigation*
	Industry	Hydropower Waste disposal**	Steam power in kitchen Mining** Cooling Processing** Hydraulic transport	Hydropower Waste disposal**
	Infrastructure	Navigation Recreation Aesthetic enjoyment Waste disposal**	Drinking Domestic uses Public uses in settlements	Navigation Recreation Aesthetic enjoyment Waste disposal**

* – highly consumptive use; ** – heavy impact on water quality

Table 2. Matrix for identification of primary barrier group in implementation of water awareness at different activity levels (based on da Cunha 1989/1990)

Type of barrier*	Perspectives/Dimension			
	Strategic	Societal	Organisational	Conflict-solution
Structural *s*-level ↑ ↓ Individual *i*-level	Problem perception and recognition Communication modes Degrees of freedom for action	Political goals Actor/Group preferences Emotional differences deficiency	Institutional setting Power distribution Public participating	Ideological differences Vested interests Cognitive differences

* recognised as primary barrier group for implementation of water awareness at different statistical s-i levels

Table 3. The categorisation of water resources by reference to use classes (based on Milly et al. 2008)

Water resources		Barrier to use
Classes	[1,000 m³ *per capita* per year]	
1 2 3 4 5	>10.0 10.0-1.6 1.6-1.0 1.0-0.5 <0.5	Limitations in logistics management Fundamental management problems Water stress Chronic lack of water Barriers to management

Table 4. Categorisation in relation to the scale of flow of water resources (based on Rockström, Falkenmark 2014 after: WRI 2014)

Water resources		Intervals for values of water resources [1,000 m³ *per capita* per year]	
Classes	Sections	Rockström, Falkenmark (2014)	World Resources Institute (2014)
I	Below a barrier of water management	≤0.50	≤1.00
II	Frequent lack of water	0.50-1.0	≤1.00
III	Water stress	1.0-1.60	1.1-1.70
IV	Fundamental problems of resource management	1.60-10.0*	1.70-5.00
V	Limited resource management problems	1.60-10.0*	5.00-15.00
VI	No fundamental management problems	≥10.0	15.00-50.00
VII	Plenty of water	-	≥50.00

* – Rockström, Falkenmark (2014) introduced the same limit values (thresholds) in classes IV-V

newable water, considered in a traditional way (treating water as a technical factor), or else in an ecological way, whereby agricultural output is accounted for, *inter alia.* Need for water presented with the aid of a block diagram includes and illustrates two cases, of which one is traditional, relating to endogenous water resources available for use as opposed to lost; and the other is ecological, in that it includes water available for plant production (in forests, fields, and meadows), and accounting for production losses as given by the difference between outflow, precipitation and evaporation.

To sum up, in the 1980s there was a (still-topical) major change in approaches to water-resource use, with decision-makers taking more and more account of new developments in water management, and renewable resources taking their rightful place in line with economic, social, and ecological considerations.

MEASUREMENT OF THE DEFICIT IN RENEWABLE WATER RESOURCES

The growing deficit in flowing and underground water resources was raised by the UN as a worldwide problem as early as in 1992 at the Rio de Janeiro "Earth Summit". However, the resulting *Agenda 21* (Adoption of an Agreement on Global Environment and Development) was not at that stage determined enough in its justification for the need to confine civilisation's development by having it save on water use and manage resources better in areas of water deficits, where climate change is also contributing to water shortages.

Further reports, signed declarations and report syntheses, including reports from Kindler (2009, 2014, 2016), the 2013 IPCC Report, and the Millennium Development Goals (2015) also confirm empirically, growing shortages of water as reflections of ever-greater instability of the climatic and hydrological cycles. These shortages are exacerbated by the increasing demands for water imposed by different branches of the economy, by agriculture, and by human needs in general.

The 3rd World Water Forum was hosted by Japan in 2002, at Kyoto University.

The Forum undertook an overall assessment of the Earth's resources of water in the context of risk and demand, *inter alia* for the melioration or irrigation of areas producing crops. Drip and areal irrigation systems were found to increase the biomass of above-ground parts of plants and roots, as well as transpiration, interception, and guttation. The amount of water taken up by plants determines water-balance structure (bearing in mind the retaining or expending of resources), while limitations on farm output in times of deficit are considerable, especially in the semi-arid zone. Evaporation in areas of rice cultivation is found to be increasing (de Wit 1958, 1965, 1969; Stanhill 1960).

Crop yields (Q) can be calculated by reference to the simple formula in Equation 11. i.e.:

$$Q = A_1 \times W \tag{11}$$

where: Q is the [kg·ha^{-1}] dry-mass yield of plants; W the cumulative amounts of water transpiring [in mm]; and A_1 a coefficient [kg·ha^{-1}·mm^{-1}].

It should be added that Stanhill (1960) was able to show how the value of the coefficient A_1 in the case of grasses (including rice in paddies) – depends on climate and latitude.

The amount of water abstracted for economic purposes is increasing, thereby lowering water tables and reducing the flows of rivers (especially the smaller ones).

The Kyoto Water Forum included discussions on ways of calculating total amounts of water needed for biomass production (including food production). In the process by which plants develop, an important role is obviously played by evapotranspiration. However, beyond that, "technological" water is needed in livestock rearing and in the processing of food products. The amount of water needed to achieve a unit of output is, as Hoffman et al. (2000), Hoekstra (2003), and Chapagain and Hoekstra (2004) declared, the so-called virtual water, as described by the water footprint. This change in how water-resource use (and especially the consumption of high-quality water) is assessed is being debated more and more, even though it was once ignored. However, if consideration is given to unit demand for water in the production of food and industrial goods, it is clear that requirements are greater, as Table 5 makes clear.

A further global milestone came with the introduction of a key new process, Integrated Water Resources Management (IWRM). In IWRM ecological value is assigned to water, and it has become a priority in relation to the UN's Sustainable Development Goals.

In the wake of this activity, work commenced on potential water deficits and shortages, including a classification of relative availabilities.

The synthesis adopted thus far on the basis of reports from the European Environment Agency (2012a-b, 2018) points to progress achieved with access to water, a service offered to countries by the European Commission. A good example is also found in the Rome Report of the FAO agency responsible for food security. However, it needs to be realised that the climatic and hydrological balance and other proposals put forward by Budyko (1977, 1986) are too simplistic to suffice for long-term assessments, e.g., in regard to hydrological drought. In contrast, they would seem adequate to describe meteorological drought (Tallaksen, Van Lanen 2004).

The scale of assessment of water resources in relation to consumption is not uniform, however; though it may for example be presented in the form of an index of the economy's need for water. On average this would be 80-100 *L per capita* per day, according to the WHO, after Mikulski (1998), Gutry-Korycka (2018), etc. Beyond that, a measure of water resources in the economy may involve the index of water stress, denoting a water deficit (shortage) unfavourable from the points of view of people and plants and animals. Excesses of water (the inundation or submerging of soils and vegetation) disturb physiological processes, limiting or preventing crop production and affecting the amounts of fresh or dry biomass produced.

Those considering the measurement of amounts of renewable water resources should account for the average resources of flowing water as the so-called unit resources of water expressed gross and per capita. Gutry-Korycka (2014, 2018) holds that the post-War years (1946-2014) in Poland saw this amount vary over the range 1,090.6 m^3 per capita (in 1990) to 2,767 m^3 per capita (in 1948), with an average per-capita value of 1,824.3 m^3. Gross water resources in successive years reflected variability in replenishment by precipitation combined with the consumption of water and increasing human population size.

In the face of modest renewable resources at times of water deficit, in-depth work on the use of green, grey, and blue waters is needed, in areas of advanced urbanisation in particular. Confining considerations to blue water and management is not adequate. It is also important for a distinction to be drawn between permanent water shortages brought about by human activity, and drought that is the result of climate change.

The importance of water to the economy and to the existence of human beings and nature is clear enough. It is therefore worth citing the most recent (44th) Rome Report from the FAO Committee on World Food Security, which refers to environmental threats diagnosed with full argumentation regarding their importance to development and the unfavourable influence exerted on long-term change. Reference is made there to new proposed solutions, and to changing renewable resources (von Weizsäcker, Wijkman 2018). This direction is congruent with the content of the Declaration from the Earth System Science Programme (ESSP) issued in 2008 as the so-called "Cape Town Declaration" (Ericssen 2008). Directions for contemporary science and geopolitics are also set out, with a view to urgently making humankind more aware of the threats facing the Earth as a whole. Much emphasis is put on indicating key ways in which to counteract the chaos present in urban and rural development around the world, with reference made to the so-called "soft development factors".

Furthermore, in the English language the concept of well-being has been introduced in reference to health, family, and quality of life (Czerny 2008; Gutry-Korycka 2009; Delang 2018). Among the key factors underpinning existence in this conceptualisation are access to housing, and the means of obtaining energy for heating and the preparation of meals. There is also a strong acceptance of the need for factors helping to safeguard life, such as drinking water, food, cultivated land, means of sanitation, and access to toilets, medicines, and healthcare.

In summary, Drogers and Immerzeel (2008), Brown and Matlock (2011) stress that the matter of access to water, especially that needed for drinking, sanitation and irrigation, has assumed priority status, especially in areas faced with considerable shortages.

Optimal use of water resources to meet a whole range of municipal, agricultural, industrial, energy, recreational, and tourism goals should accord with appropriate water-management decisions based on knowledge, targeted action, and astute strategic thinking. The fundamental resources of water are what are termed "blue" by Falkenmark (1986), and Falkenmark and Rockström

(2004). This water may be augmented by so-called "grey water," i.e. effluent from any uses that do not involve faecal contamination. At one time, precipitation was not regarded as a significant contributor to the renewability of water resources. Today, however, greater deficits in the availability of blue water dictate that grey water should undergo treatment to be reclaimed as a resource. Grey water originates as effluent from urban infrastructure, as runoff from peak high-water events, and as a component of the superficial groundwater layer. Volumes of grey water are determined by processes taking place on the land surface in urban areas, tending to augment short-lived retention at the surface, reflecting the presence of infrastructure. However, this water can also be used, for example, as a component of green water.

Efforts to prevent ever-greater shortages of water in urban areas, involving economic impact, require instruments effective in the management of renewable resources, as well as relevant regulations. Crisis surrounds the greater demands for water exerted by the populations of cities, as opposed to the efficiency of urban infrastructure. Shortages of water are thus increasingly a significant barrier to society's sustainable development (*World water supply and demand in 2025* 2000; Rijsberman 2006; Stern 2006; *Więcej niż niedobór: władza, ubóstwo i globalny kryzys wodny* 2006; Drogers, Immerzeel 2008; Kundzewicz, Kowalczak 2008; Gerten et al. 2015; Steffen at al. 2015; *The Milennium Development Goals Report* 2015). Barriers associated with water shortages include a value for the index of water stress that represents an unfavourable situation for the soil and the plant canopy. In turn, there may be a water deficit in the context of a drought period; or else an excess leading to flooding and puddle stagnation that is unfavourable for retention by the soils and plants (green water).

Water stress has been related to human beings by many authors (including Milly et al. 2008 and Rockström et al. 2009), with quantification mostly involving a subjective 5-point scale (Table 3).

A new approach to the protection and use of water resources (and the reduction of deficits) was announced by the UN in 2005, in the context of the International Decade for Action "Water for Life". Regulations for the protection of water resources and the right of human beings to potable water and sanitation were in turn agreed upon in 2010 (Huntington 2010). Natural rights form part of classical ethics and are near-ecological in character; because humans need water, they have a fundamental right of access. Of course, giving effect to such concepts inescapably implies a just division and assignment of water resources – a matter that assumes considerable significance where deficits are common. Likewise, Pope Francis in his *Laudato Si* Encyclical of 2015 drew attention to the exhaustion of water resources through excessive consumption and worsening deficits, as well as the matter of the deteriorating quality of those resources. It needs to be added that prospects for socioeconomic development, including water management, are very much linked with the future management of resources, guided by key premises regarding water saving, and the fact that water is a common good that every human being has the right to use (Gutry-Korycka 2017).

The optimal future solution for limiting water deficits entails equilibrium among the economic, social, and ecological pillars, (i.e. sustainability), thereby then providing a basis for the achievement of an appropriate, if limited, degree of tolerance most closely resembling nature's principles and processes.

Development and urban sprawl go hand in hand with population growth and ever-increasing population densities in many parts of the world, leading to a rapid reduction in water resources, and concomitant deficits. A question therefore arises concerning the directions that might be followed to ensure reduced use and consumption of water. The need for conservation applies to drinking water, precipitation water and its retention, the water in aquifers, and the water assigned to the irrigation of plants, whether naturally-occurring or cultivated. A primary constructive action would be to ensure the collection and retention of water at or close to the places where precipitation falls on roofs, terraces, and balconies in continuously or partially built-up areas, but also on playing fields, lawns, and squares; all the time seeking to ensure that water is not wasted through rapid (and also polluted) surface or near-surface runoff, from where it goes to sewers or the storm drainage system.

Estimates made in cities suggest that the index for surface cover of an impermeable nature is 100-150 m^2 per person on average, in Poland; whereas the WHO suggests that this index should be less than 50 m^2 per person on average. Urbanisation is associated with ever-greater sealing-off of the substratum, which increases detention of water on the surface (wetting), while the resources available for human uses are reduced markedly as a result (Gutry-Korycka 2003; *Natural Infrastructure: Investing in Forested Landscapes for Source Water Protection in the United States* 2013; Gutry-Korycka 2018). It needs to be stressed that the utilisation and waste of water in cities is of key relevance to sustainable development, relating to rational intake and use in the forms of production and consumption. The objective is to counteract wastage of water with the possibility of uptake via infiltration and retention, in this way effectively ensuring that, irrespective of the season of the year, overburdened and overstretched pipeline waters can be replaced by precipitation. Gardens hanging on walls or located on roofs and terraces join gardens, parks, squares, etc. as biologically active areas in which evaporation and transpiration are enhanced. Economies in the use of water resources can be achieved in this way, as can increases in available resources, without any increase in fees paid. In turn, what is negative in the most general sense is the influence of construction on the natural environment and its resources. Urban areas use 1/3 of all water (more than 35% according to the EU). There is thus a need to make the public aware of the benefits of a joint approach to multi-family housing construction for the renewability of resources.

Widespread understanding of the "drop to drop" concept represents a proper direction towards more systematic economising on water. With this idea, waters not previously quantified (e.g., water and wastewaters from households) are treated as useable resources, representing an additional element among the renewable sources of water. Each user may have the impact of reducing small-scale retention, given that more than 70% of their property on average is no longer a biologically active surface capable of playing an active part in the cycling and retention of green waters through increased evaporation and evapotranspiration.

Table 5. Average capacity of virtual water footprint for the selected products (based on Mioduszewski 2006)

Product/weight or volume	Capacity of virtual water [L]
sheet of paper A4 (80 g/m^2)	10
slice of bread (30 g)	40
apple (100 g)	70
glass of beer (250 ml)	75
glass of wine (125 ml)	120
glass of coffee (125 ml)	140
glass of milk (200 ml)	200
hamburger	2,400
cotton shirt (500 g)	4,100
pair of shoes (leather)	8,000

From the point of view of the macro-use and non-renewable consumption of all water resources, the water management balance can be a monitoring tool to track various objectives and priorities (municipal, industrial, agriculture, forestry, or fish-farming, wherein both blue waters and green waters are used).

To increase amounts of green water needed by Poland's agriculture and horticulture as in the Netherlands, grey water, derived from the discharge of groundwater and somewhat-polluted surface runoff into watercourses, can be used. During the growing season, crops are irrigated with water resources more available and less costly than potable water.

Most forecasts indicate that the greatest future use of water will be in agriculture. If cultivated plants have sufficient water, then the overall increase in yields will depend on the potential transpiration, and hence the rate of conversion of water into water vapour. The demand exerted in this context during the growing season varies from species to species. Water management seeks out the best solutions in relation to species achieving ever-greater yields, or amounts of fresh or dry biomass. Yields will be higher the greater and more stabilised the humidity of soil. An example is supplied by yields per hectare in relation to permissible variations in humidity. Generally speaking, the water used in agriculture (be it grey, green or blue) is almost 100% irretrievable as a resource, being liberated by plants via the stoma and passing to the atmosphere, thanks to the processes of interception, transpiration, guttation, and dew formation.

Work by Łabędzki et al. (2010, 2014) shows that precipitation totals and distributions during the growing season (for sugar beets, for example), with a two-month time lag, determine the relationship with soil moisture, though each crop reacts to water amendments at a different rate. As Chapters 4 and 5 showed when dealing with the description of hydrological processes, reference should be made to the mid-1970s, when about 70% of water used (8,101,300,000 m^3) went to industry, with the municipal management in second place at about 17%). That left only 13% for agriculture at the time.

Subsequently, marked changes in these proportions were planned with agriculture receiving the largest share. Plant species differ in how they use water to produce biomass, typically using about 200 g of water to produce 1g of dry mass; the amount can be much greater: up to 1,000-1,500 g for some species. Thus, there has been a search for less thirsty crops, given the progressive water deficits that have been observed. This need is all the more relevant given the inevitability of human population growth, which will demand further increases in yields and harvests, all naturally at the cost of water used.

Drought during the growing season is a major problem that extends beyond the hydrological realm into the economic and ecological domains. Things are only likely to get worse as precipitation anomalies seem to worsen, with the direct result of a potentially disrupted hydroclimatic balance. The negative impacts of water deficits on soil and plants (and rivers and superficial sources of groundwater) can threaten crop yields, reducing them by more than 25%. In turn, retention in a given area may reach a critical state (Kasperska-Wołowicz, Łabędzki 2003; Łabędzki et al. 2010).

Agro-climatologists also adopt a standardised climatic water balance as a measure of shortfalls in water supply, (termed *KBW* in Polish) as was noted above (after Łabędzki 2003; Łabędzki, Adamski 2010; Wibig 2012; Wypych, Kowanetz 2017). This measure is based on standardised precipitation and soil humidity, capable of being described in various ways, e.g., empirically similar to the model arrived at by the French climatologists Turc and Pike (1964 after: Dooge 1982). As verified in the northern Sahara, this holds that:

$$CWB = \sum P_r - 0.4t + 15^{-1}I + 50 \qquad (12)$$

where: $\sum P_r$ is the total for corrected monthly precipitation totals [in mm]; t is the mean monthly value for air temperature [°C]; and I the monthly total for overall 24-hour solar radiation [expressed as calories per cm^2 per day].

The time scale of saturation at which drought in the soil can develop is 1-3 months, after which hydrological drought ensues, possibly persisting for several months or even years. Wibig (2012) estimates the variability in soil-humidity conditions by reference to the Standardized Precipitation Evaporation Index (*SPEI*). It is recommended that evapotranspiration be represented as a function of potential evaporation (after Thornthwaite, Mather 1957; or Penman 1956). Humidity is then classified in relation to *SPEI* by reference to 9 intervals for *CWB* values, reflecting the difference between the mean corrected precipitation total (P_r), and the mean total for potential evapotranspiration (E_p), also known as indicative evapotranspiration (in mm), with:

$$CWB = P_r - E_p \qquad (13)$$

Use is also made of heat-balance equations, with net radiation determined, along with all the component parts (heat fluxes), as calculated in Equation 4 above. *CWB* assumes positive or negative values, the latter indicating drought during the course of the hydrological year. Persistent shortfalls of water resources in agriculture are likely to become increasingly evident. *CWB* values, and hence climatic shortfalls in precipitation, depend on the method applied in calculating indicative evapotranspiration (E_{pt}). An absolute assessment of the water involved in plant production may be achieved by reference to the difference between precipitation and evapotranspiration.

In summary, users of both real and virtual water are not just the population, or industry, or farming; but also include forests and nature. This truth clearly influences the cycling of water in drainage basins, and can be used effectively by those seeking to determine a balance for water retention that takes in both quantitative and qualitative aspects of the resource. What is involved here is a conscious steering of the water-balance structure in agricultural areas in relation to the uses of surface water and near-surface groundwater. Waters of good quality lying at greater depth, and only marginally renewable, should in turn be the subject of special, permanent protection.

6. THE RENEWABILITY OF WATER RESOURCES AND THE IMPACT OF CLIMATIC WARMING

Fluxes of water and heat through the soil-and-plant column and the drainage basin are subject to the influence of climatic conditions that are *inter alia* shaped by the chemical composition of the atmosphere, which regulates heat (and therefore energy) exchange processes. These processes themselves change at various rates because of rising emissions of greenhouse gases, which are associated with greater use of energy from burning fossil fuels. Deforestation, the intensification of farming, the activities of industry, and the transportation sector are all contributing to greenhouse gas emissions and climate change.

As indicated beginning in the early 1980s by various leading scientists, climate change is undoubtedly influenced by the anthropogenic factors referred to, as official reports from the IPCC (e.g. in 2013 and 2014) make clear. This fact has gained confirmation empirically, despite opposition from some people in various countries.

As Dooge (1982) stated, the influence of global climatic warming opened a key stage in the development of a new and crucial area of hydrology. It provided a kind of "rejuvenating elixir" for disciplines engaged in the study of water(s), as well as for the closely related fields of meteorology, geodesy, cartography, and geophysics. Here, simultaneously, was a great methodological catalyst, especially where mathematical modelling was concerned. The integration of Earth-sciences disciplines was developing around a matter as crucial as the continued existence of the human species (as well as other species), and although naturally renewable, water was obviously one of the critical factors.

The linking of Global Circulation Models (GCM) scenarios with hydrological models of drainage basins requires the application of methods for mathematical rescaling of the transition of semi-empirical methods from data of low temporal and spatial resolution to high-resolution data (Kaczmarek 1996; Gutry-Korycka 1996; Lenartowicz, Gutry-Korycka 2009), etc. The confirmation of the influence of global climate change on hydrological systems was essential on both the mesoscale and the regional scale. However, the rates and directions of the changes involved may be related to different processes in different ways. Matters exerting an influence here include model precision, methods of estimation, and the measurement data used in projections for determining as realistically as possible the probable changes in system dynamics (IPCC 2000, 2007, 2012, 2014).

Among those addressing such issues were Gleick (1987), Ojima (1992), Lettenmaier (1994), Kaczmarek (1996) and Gutry-Korycka (1996). They all drew attention to the crisis facing water, given assessments suggesting major changes in resources. Such findings offered both impulse and inspiration for digital models of global climate to be developed, with spatially-dispersed or clustered parameters, and a possibility of achieving more and more accurate long-term forecasts (with development scenarios for the economy generated ever-more effectively). Thesemodels benefitted from new digital methods, multidimensional computer graphics, areal and satellite imagery of finer and finer resolution, etc. With measurement data being obtained with ever-greater precision, regional scenarios taking shape (with their "sub-scaling methods"), deterministic or stochastic drainage-basin models can be verified with respect to precipitation and outflow, and *inter alia* the water balance and/or climate-related aspects.

The advances in knowledge have been proving exceptionally valuable, while mathematical modelling has become more and more reliable, with operative versions now suitable for use in the forecasting of processes occurring on various scales.

Quantitative and qualitative assessment of changes in the proportionality between different forms of retention and river outflow were measures of what consequences global warming of the atmosphere was having for water resources. The ongoing developments in this field were thus very much targeted and fully justified in substantive terms. Often what were involved were regions and basins already poor in water resources, with the consequence that they might be particularly vulnerable to changes in water cycling. As levels of solar radiation increase, and along with them the temperature and humidity of the air, there must be a reduction in the magnitude of water resources and their availability, and hence also no guarantee that water will be available at all. However, in the circumstances of a changing climate, this kind of assessment is not an easy task, because water within each area, region or basin is in constant circulation. That means that the reserve available at any given moment is actually in a constant state of flux. Amounts of water in circulation determine the size of the renewable resource. The first measure of this quantity adopted was the long-term (multi-annual) mean obtained for total amounts of precipitation falling in given years. In contrast, the mean expressed on an areal basis has tended to involve the long-term river discharge, or else has been seen from the point of view of the water-management balance in which there is a description of characteristics of resources as: average or low, disposable, inviolable, guaranteed or other, from the point of view of the demand for economic use.

The first attempts at numerical simulation were made in the USA, Canada, Europe, Australia, and Japan at the end of the 1980s. They showed that as a consequence of global climatic warming renewable water resources during warm seasons might become 15-30% smaller than in the baseline period, while those in cool seasons might increase at various rates. Given the increased demand for water imposed by the economy, urbanisation, agriculture, livestock rearing, drainage, irrigation, the power industry, other industry, and construction, permanent or at least periodic shortages of water would be implied.

Numerical simulations (of either the equilibrium or dynamic types) that can be used to assess changes in renewable resources of flowing water arise from combining Regional Global Circulation Models (GCM_R) with a hydrological model of the conceptual type in which spatially-clustered or dispersed parameters describing processes are represented physically and dynamically with an appropriate time-step, along with an adopted scenario for economic development. Generated fields for air temperature, atmospheric precipitation, heat-balance components, field evaporation, and evaporation from the surfaces of open water reflect the circumstances in a meso-scale area that is the subject of analysis, in the form of spatial breakdowns that are set against long-term (20- or 30-year) reference means adopted as stationary values. However, this condition is not always met.

In the context of mathematical modelling what can be addressed are not merely shortages, but also surfeits, of water in the form of peak high-water events of increasing regularity or height, induced by precipitation, by a combination or precipitation and thawing, or by stormwater flows.

Circumstances of the inadequate or excess presence of water resources are perceived in the context of the threats to civilisation they potentially pose. Thus, these deviations from norms have often become the centre of attention nationally or internationally at too late a stage, especially for those who are actually using or managing the given water.

In the context of this article, there is a need to review the historical background, in order to understand the developmental stages that have been experienced. Many problems, which were once novel, now underpin contemporary understanding of mechanisms and global climatic processes, as well as the means of adaptation, albeit under economic conditions that remain as yet unknown.

So, what are, and what will be, the responses of hydrological systems to future global changes? If humankind elects to ignore the problem (as is hinted at) then catastrophe awaits our planet. Renewable resources of water (including groundwater) are already declining, with droughts and heatwaves increasing in scale and frequency, while both soil humidity and precipitation totals are in decline.

The causes of increases in the Earth's temperature (and hence premises underpinning climatic warming), have been of interest to geophysicists for almost 200 years. This view is according to Malinowski (2019), though it was not confirmed by Biswas (1970), who nevertheless referred to the French mathematician and physicist Fourier (1719), with his collection of temperature data. This work may be treated as a precursor to the discovery of the mechanism underpinning the Earth's energy balance, as well as the way in which it may be assessed. In practice, however, about 150 years would pass before the issue was taken up by Anglo-Irish natural philosopher Tyndall, who noted the key significance of CO_2 as a greenhouse gas, while also referring to methane and water vapour.

It is also worth citing the views of Belgian scientists at the University of Liège, Spring and Roland (Demarée, Verheyden 2016). In 1896, these authors were cited by Arrhenius. They were interested in emissions of greenhouse gases to the Earth's atmosphere. In addition to CO_2 and water vapour, infra-red radiation is absorbed as a result of a rise in equilibrium temperature. Of course, were there to be no natural greenhouse effect, life on Earth would not be possible at all; this was something that Arrhenius did indeed refer to, having discovered it at the same time as the ozone layer. Moreover, at the end of the 19th century it was shown that concentrations of CO_2 were continuing to rise as a result of the burning of fossil fuels. This finding formed a basis for the estimation of changes of temperature (Δt) on Earth as more or less given by $\pm\Delta CO_2$. Continuing with this thread, it is important to recall the American physicist and astronomer Langley, who studied the transfer of sunlight and infrared radiation through the atmosphere at high latitudes. Malinowski (2019) made the connection to polar or Arctic strengthening of the greenhouse effect. In the 1930s, the British physicist Callendar was a pioneer in explaining how temperature in the atmosphere might rise in connection with the increased concentration of CO_2 in the air.

Much later, American research on the isotopic composition of CO_2 in the atmosphere, as well as the oxygen present in ocean sediments and ice cores, confirmed the dependence on the burning of coal and other fossil fields, which was directly responsible for atmospheric concentrations. Earth's sensitivity, even to limited climate forcing, is great, while disturbances and their effects expand, up to the planetary scale.

To sum up, global warming continues, and scientific uncertainty about changes in renewable resources of water is ever greater, given the dynamic configuration that the climate system represents. Re-expressing these kinds of problems as the economic costs of causes and effect, Stern (2006, 2019) expressed the view that net global emissions of greenhouse gases must fall to zero by 2050, to prevent air temperature rising by more than ≈2°C. Management of water resources was then assigned fifth place among six sectors of the economy crucial to the achievement of sustainable infrastructure development. These are, in rank order, power supply, urbanisation, food production, land use, water management, and industry. Integrated together, since 2018 these sectors form a new concept of macroeconomic activity known as the New Climate Economy. Water resources obviously play a key role.

7. A NATURE-BASED SOLUTION (NBS) CONCEPT FOR WATER RESOURCES

The historical review of the development of science, as well as contemporary activity and international climate policy offers the key challenges for programmes dealing with water and water resources (Section 3). Shortages or periodic excesses of water are among the threats to civilisation posed by the natural environment, though a quasi-equilibrium state of the Earth is still maintained (Falkenmark, Rockström 2004; Huntington 2010 et al.). Key resources are those of water and food, as well as biodiversity at the levels of the species or ecosystem. Given the temporal dynamics of phenomena in the environment, as well as causes and effects, it is anticipated that there will be changes over a longer time period extending to 2030, 2050, or even 2100.

Two pyramids (as in Fig. 6) represent the virtual division of the world into two (northern and southern) parts, which differ across seven factors (i.e. the age of society, level of wealth, resources, type of influence due to climate change globally, technologies, and research), as well as features of the world's sustainable development in line with scales of development ranging from the local to the global (*Sustainability Science* 2001).

Lewis (2012) used an edition of *Nature* to justify and account that, given the presence of climate change, we should soon be needing an expanded network serving the interests of planetary research, to include problems associated with various aspects of water resources.

However, international organisations like the UN, UNESCO, ICSU, UNEP, WHO, IGBP, FAO, IPCC, FUTURE EARTH and others have based their long-term forecasts for resources on the period extending to 2050.

Recent (2013 and 2014) IPCC reports make reference to Rockström et al. (2009), Rockström and Falkenmark (2014), Vörösmarty et al. (2010, 2013), and Steffen et al. (2015), expressing the growing risk that the Earth's capacity might be exceeded through excessive consumption of water, by what can be regarded as non-economical use of that resource, and the destruction in both qualitative and quantitative terms of the natural environment, including plant cover, soil, and even geological structure.

In light of these concerns, it has proved possible to identify sustainable routes to development, as well as barriers that should not be crossed. Many researchers, including Gallopin (2012), Cosgrove and Cosgrove (2012), Bierkens (2015) and Steffen et al. (2015) warn against excessive consumption and use of water resources. Moreover, an accelerating process of global climatic warming overlies the hydrological cycle, prevailing over all its components. Meanwhile, the limit of sustainability for water resources has not yet been crossed, notwithstanding the ever-growing risk that shortages will arise; on the other hand localised problems with excess water can be observed as ice, glaciers, and snow melt, and as flood events, intensify, not least on account of higher precipitation totals.

In applied science, recent years have seen an opening-up of new possibilities by which water deficits may be limited, accelerated, delayed, or contained both spatially and temporally. The use and management of water in urban and rural areas to try and economise has had further influence, in the appearance of a new area of knowledge (i.e. "Nature-based solutions") advocated by the last UNESCO International Hydrological Programme Report (NBS 2018).

The balancing of water resources available for use may prove helpful during a period of deficit, when it becomes imperative to incorporate mechanisms of directing processes of mass and energy exchange, in particular with losses of water brought about by planted vegetation or that growing naturally (Veldkamp et al. 2015). This balance requires linking identified resources and needs for water arising from the economy, as well as management within the framework of land-use planning that references the main economic, political, and social considerations. Integrated management of resources is especially important in urban and industrial areas, including the building, redeveloping or revitalising of stormwater drainage, with the aim of the infrastructure not merely moving water but also supplying capacity for its retention. Most generally, it is essential that outflow from impermeable surfaces like roads and pavements should be redirected, for example, by increasing the permeability of surfaces on squares, car parks, sports fields, etc. It is in this kind of activity that we see appropriate adaptation to climate change (Burszta-Adamiak 2015, 2018). Water management is far more effective, and far easier, where there is a centralised system serving this purpose. Rainwater runoff and water from melting snow and ice can in this case be transferred to reservoirs, and resources recouped by way of systems of transfer to artificial ecosystems set up in the immediate vicinity of buildings.

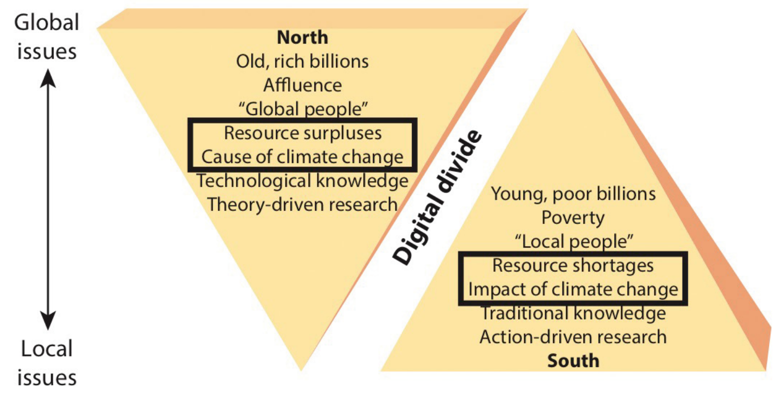

Fig. 6. Sustainability science within a divided world (Science 2001, vol. 292, No 5517, p. 641-642; boxes added by the author)

The 2018 report on NBS makes no mention of the potential for use of grey infrastructure and grey water. Thus, the following describes certain NBS directions and solutions for the use of water resources that enjoy that status on account of their being inspired by the laws of nature. In terms of broad scope it is green infrastructure that is being referred to, which is capable of operating in parallel, in a measurable and beneficial way, with grey infrastructure; where hydrological processes relating to the quantity and quality of water are integrated. The principal objective is to find the most appropriate linkage between grey water and green water, so that maximum benefit can be drawn from operating the system and its capacity, with costs minimised, and the number of components limited.

For an example, we may refer to a model for irrigation by means of the optimisation of efforts to achieve harmony (Čistŷ 2008) in the operation of irrigation systems. Work by Kovalenko and Mikhaylov (2008) relates to the control of irrigation in a system, under conditions of minimised uncertainty of supply.

It needs to be added that, for example, the temporal and spatial modelling of very variable agro-hydrological processes in a drainage basin often requires 24-hour meteorological measurement data; the lack of these data precludes necessary simulation and forecasting in the service of decision-making (Kuchar 2004).

The latest NBS generate environmental, economic, and social benefits relating to the use of water resources, especially in terms of health and sanitation, as well as food, water, and energy security. These ideas promote economic growth while maintaining biological diversity, and the recovery of species at risk for extinction, leading to the protection of whole ecosystems

As opportunities for NBS to be applied are sought, reference will need to be made to the fulfilment of principles set out in the UN's (2014) Declaration on Water. The assumption is that each Member State is obliged to increase water resources through natural renewability, with efforts also made to achieve improvements in water quality, and long-term sustainability of use. For their part, EU Member States have been called upon since 2011 to rapidly and permanently achieve sustainability vis-à-vis resources of water (and the ecological state thereof), above all through consumption that is adjusted to ensure many different sectors of the economy can have their demands met.

Particularly noteworthy are the conceptions for water management in EU Member States set out in the Framework Water Directive, and thus upheld by both the European Parliament and the European Environment Agency. NBS that govern the hydrological and hydroclimatic cycle should be able to supply economic, social, and ecological benefits that provide for the optimal utilisation of water in line with the needs of food, energy, and sanitary security.

The use of green and grey water in connection with suitable infrastructure makes savings possible, translating into accelerated renewability of resources, with consequent knock-on effects for financing as well.

In United Nations World of Water Development Report (2018), examples of NBS in the form of theoretical curves have been selected carefully enough to ensure the representation of benefits, above all quantitative ones concerning renewable resources in connection with long-term economic benefit. These curves appropriately correspond to actions taken, with one such presented in Figure 7 showing changes in an ecosystem's throughputs of matter and energy.

Considerable potential for NBS-type ideas can be found in references to regional- or local-scale land use, as translated into the rate of change in water cycling around the short-branch nexus (taking into account biomass increment, productivity, and evapotranspiration (Falkenmark 1989).

A dynamic water-management balance represents a proper basis for the quantitative management of water resources, for example, proving helpful in the phase of early warning and implementation, as well as facilitated decision-making for the sustainable use of resources.

Major opportunities for benefit lie in assessments of adaptations to global change where the rate and direction of change in the hydrological cycle are concerned. Post-2015 there was a particularly lively debate on the significance of water for the Earth's future. In turn, the world scientific programme Future Earth existed alongside the UN and other international organisations. Most recently (in February 2019), Japan organised the world Ecological Forum in Tokyo.

Identified among the key topics for discussion at the Tokyo Forum were food security and the depletion of natural resources (including water). The aim was to bring together representatives of academia and business, industrialists, citizens, and students. The discussion centred on solutions that might prove effective and could be implemented rapidly, in this way serving the achievement of sustainability in nature and society. A Forum was devoted to the main aim of the Global Environmental Facility, said to have »Clearly stated stewardship over the Earth in the Anthropocene Era and introduced the concept of Global

Commons« (*United Nations World of Water Development Report* 2018).

Nakamura from Hokkaido University demonstrated the recovery process in the Japanese environment by reference to many images, while also introducing how useful green infrastructure might prove in preventing natural disasters (floods of various kinds, tsunamis, droughts, etc.). Finally, there was a presentation of a relevant Programme within the International Global Environment Sustainability (IGES) framework.

The involvement of interested parties in seeking to achieve permanent infrastructural solutions in this field requires a transformation, or totally new approaches and challenges.

8. CONCLUSIONS AND REMARKS

In summary, existence in the longer term will be very much supported by the integration into economies of construction, industry, spatial planning, and the management and protection of water resources whose renewability is assured by effective conservation and limitations on levels of stress.

As with the biological approach, a broad framework of designated tasks has been adopted in line with a definition whereby the IUCN considers NBS as »actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits« (*United Nations World of Water Development Report* 2018).

If designated tasks are to be pursued effectively, there is a need for close cooperation, major financial outlays, efficient management, and most of all an awareness and understanding on the part of societies that solutions such as NBS are justified in the interests of the Earth's future, focusing on renewable resources and efforts to ensure their regeneration; which is to say a return to sustainability (for the benefit of future generations as well as ours). As a key barrier to development, water resources have recently been going through quite a crisis. That makes it important for integrated solutions to be adopted to limit negative environmental impacts, in regard to both the quality and the quantity of water. Appropriate decision-making is very much dependent on scientists' clear identification of environmental processes that play a key role in upholding renewability of use, as well as the minimising of barriers on the global, regional, and local scales.

Contemporary knowledge and technological progress, involving ICT in general, and mathematical modelling in particular, support several key tasks. Appropriate, optimal methods and solution-oriented functions need to be found, in order that many processes responsible for current changes may be assessed. And thus, it is water, present in various states in all the spheres that is of priority significance! The management of water resources in the context of urban and rural governance must limit or ameliorate negative social and environmental impacts.

Ultimately, NBS methods need to be approached with caution, separately for quantities of water resources dependent on hydrological processes, but also with respect to water quality and the processes of geochemical pollution integrated with it. Although this article does not include solutions applied in biomanipulation that resort to ecohydrological measures, these do exist.

Austrian geochemists like Weigelhafer et al. (2013) stress how necessary it is for the possibility of NBS being considered for approaches to water resources, both for quantity and quality, with limited use, for example, being made of retention.

Sectoral accessibility of water resources achieved sustainably (and hence with ongoing renewability assured) represents a key challenge needing to be integrated with a legislative approach, governance at various levels, and executive action. The quality of water resources and simultaneous improvement in the state of ecosystems dependent on water represent matters for NBS, and they need to be addressed in an integrated fashion. Legal bases are required to achieve these outcomes, but they also require ongoing hydrological and biological monitoring of waters in a near-natural state, so that the changes and benefits achieved may be assessed. NBS methods can be seen in the context of risk assessments, with the aim being to ensure maximum effectiveness (Fig. 6), but also in the context of inevitable adaptation to global change. Effectiveness in the specific context of reduced maximum flows along watercourses should represent a multidimensional function of intervention resulting from impacts of decision-making in such critical circumstances. UNESCO, in fact, appeals to each Member State to gain regional and local experience of what may be implemented in different basins, leading to cohesive spatial management plans in line with guidelines of the NBS type.

A very important aspect is, of course, the funding of planned solutions set against the background provided for in legislation, again with the aim of harmonious cooperation proceeding in different sectors seeking to achieve their aims. Pursuit of NBS to protect water resources should entail precise definition of the potential for goals and objectives to actually be achieved, with information provided current conditions and the problems still needing to be resolved, i.e. if Agenda 2030 guidelines are to be more fully realized.

The UN has among its key objectives the division of the world into two groups (Fig. 6), as well as seamless supply water to humankind and the economy, with each citizen enjoying access to water supply and sanitation services, and with efforts also made to reduce and limit the risk of natural disasters like floods and droughts. The role of ecosystems in linking new infrastructural developments with proper management lies in the way we seek to imitate the laws of nature more and more faithfully, given that this is a condition if continuity over the long term is to be assured. And in the future, key activities will entail restoration of much-degraded aquatic or semi-aquatic ecosystems to a natural state, *inter alia* for their utilitarian and intrinsic values.

A key element connected with the above aim is the redevelopment and restoration of grey infrastructure, requiring a remodelling of agriculture and redevelopment of its systems of irrigation and drainage. The reduction of conflicts between competing interests and business by way of the application of different categories of water resources is a utilitarian step in this direction. Actions to conserve and avoid wasting of water in rural, urban, and industrial areas should also be seen as very pragmatic. Green and grey infrastructure in place can do much to lower costs of water use, while limiting the optimal use of resources of grey and green water.

Efforts to manage the risks associated with, or safeguard against, floods or states of low water should also prioritise the reduction or indeed minimisation of costs. Green and grey infrastructure can combine with an economy operating in closed cycle to markedly improve NBS, in urban areas in particular; while the uncertainty surrounding integration with grey and green infrastructure in rural areas may prove more difficult (yet still a necessity). It should be added that the latest UNESCO IHP Report (from 2018) presents the most major and most effective regional examples of NBS seeking to reduce maximum flows in the cases of floods likely to occur every 20 years on average, and to limit leading factors promoting change. These examples include Green Cities in the UK, countries in the Baltic basin and northern Adriatic; northern Italy, Poland, and Scandinavian countries other than Denmark (reintroduction of river paleo-meanders along larger rivers); western France, Spain, Portugal, central and southern Italy, Denmark, Greece, Romania, Hungary, Bulgaria, southern Austria and Switzerland, as well as southern Germany (forecasting development of agricultural practices). In contrast, in NE Germany, the Benelux, northern Austria, the Czech Republic and Slovakia it is re-afforestation that is stressed; along with the development of polders in NE and N France, the Benelux and western Germany.

In line with the relevant planning, the objectives set and effective changes foreseen have a very significant financial dimension. High implementation and maintenance/operating costs translate into fees and taxes, and there will need to be special subsidies at the local, central and EU levels. Legislative provisions and authorising regulations are both essential to this kind of activity, while inter-sectoral co-operation is foreseen, or has already taken its proper place in provisions of the EU's Water Framework Directive.

The humanitarian aspect of water resources also makes it imperative that waters are protected and limits imposed, globally, regionally, and locally. These needs reflect a predicted increase in the use of water of some 20-30% (5,500-6,000 km^3 per year) by 2030. Further growth will be a function of ongoing agricultural development to safeguard food supplies and the availability of water for use in sanitation, for drinking, and for energy generation transportation.

The priority actions and solutions relating to water thus follow the concept of recycling, reuse, restoration, recovery and risk reduction, as well as improvements in quantity and quality, and effective regional-level management where implementation is concerned.

Adaptation of resources in line with the NBS concept is needed, not only to improve water management, but also to safeguard water to some critical level in the context of shared benefit. The NBS return of water resources to nature is not a panacea for everything, however, and the directions indicated here represent a long and hard road to the achievement of a desirable future situation.

Moreover, the environmental and social aspects will need to be clearly communicated and justified in the context of planned solutions and legislation, as well as management in the direction of diversification.

In sum, there is still a need to consider the directions taken and the progress made around the world in achieving stated objectives, which are based on awareness of joint action under the Earth System Science Partnerships (ESSP), Earth Environmental Science (EES), World Resources and Environment (WRE) and "Partnerships are key to success in the Future", as adopted by the UN, World Climate Research Programme (WCRP), Earth WHO, the Club of Rome and Vatican World … 2013, and *Laudato Si* of 2015), as well as many other documents and scientific papers (Couwe 2009), plus works published to popularise the idea.

The new trends in hydrology, water management, hydroengineering and technology will become elements of contemporary science and practice.

Efforts to explain the causes and effects of contemporary development demands inter-disciplinary or trans-disciplinary approaches. It will be necessary to continue with forecasting dynamic processes of water circulation, as these operate on the global, continental, regional, or local scales. For these goals to be achieved it is important that there be widespread awareness of choices, confidence on the part of society, and an identification of critical points (or indeed tipping points) relevant to geophysical, biochemical, biological, and economic systems in a multidimensional configuration, with water resources connected to the regularities that govern their renewability.

For life on Earth to survive, it is necessary that the crisis surrounding water resources be addressed to the extent possible. It is known that about 2.5 billion of the world's people live in areas that are poor in water resources; while long-term forecasts (only in fact extending to 2030) suggest that we will experience a decline in the availability of water of ≥40%. If present trends are maintained, they imply a 2050 situation in which more than half of the human population will face the threat of permanent deficit of fresh water resources. Thus, there is a clear imperative for actions that will reduce this risk. Can the situation involving unsustainable management of water resources somehow be turned around? Certainly, it will be difficult to achieve, if even possible, given that widespread awareness, combined with knowledge and experience, will be essential.

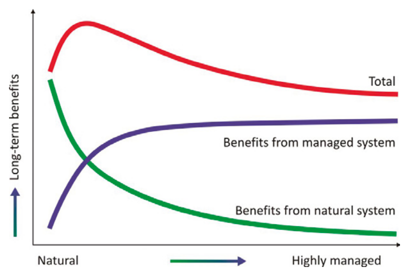

Fig. 7. Change in benefit flows with ecosystem modification (based on Acreman 2001)

The NBS concept developing currently may be understood in two ways: as nature for water, and as water for nature. In both cases, the beneficiaries are water resources, curtailed shortages and deficits, and hence enhanced protection.

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The influences of meteorological and hydrological factors on the operation and performance of a semi-natural stormwater reservoir

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ABSTRACT. The aim of this research was to determine the influences of meteorological and hydrogeological factors on the water level of a rainwater storage and infiltration reservoir. The examined reservoir is located in the urban and industrial area of Krakow, on ground owned by the Polish State Railways (PKP), Kraków-Bieżanów branch. We analyzed a range of climatic (precipitation and evaporation) and hydrological factors (water stage in the reservoir and groundwater level) and their inter-relationships to determine their influences on the water depth regime in the storage and infiltration reservoir. Based on our results, the increase in the water table level in the reservoir is connected with the increase in the groundwater level and it is observed in the spring and summer periods, when meltwater and stormwater enter the reservoir. At the end of July, the groundwater table level increases because of excessive rainfall events. Throughout the entire experimental period, the reservoir was fed by infiltering groundwater from the upper parts of the basin. The water depth averages in the reservoir were closely correlated with the average groundwater table levels, the sum of precipitation from the week prior to the date of the examination of water depth in the reservoir, and the sum of potential evaporation in the given week.

KEYWORDS: storm reservoir, heavy rainfall, best management practices, infiltration.

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1. INTRODUCTION

In the modern world, human economic activities play an increasingly large role in the changes in hydrological conditions in anthropogenically transformed basins. Thus far, human activity has caused several disruptions to the water circulation and hydrological regime in the context of 24-hour cycles, seasonal cycles, and cycles lasting for many years. The effect of these activities is the number of anthropogenic transformations evident in changes to the retention properties of basins. Most frequently, these changes are multifaceted and difficult to assess objectively as there is no record of the natural, initial conditions (Gutry-Korycka, Ciepielowski 1993). Urbanisation and industrialisation have a particularly adverse effect on the hydrological regime (Byczkowski 1997). Urbanization tends to substitute natural vegetation with impervious surfaces, thus reducing infiltration (Burszta-Adamiak et al. 2019). It also tends to eliminate natural retention ponds and to rectify river courses, thus greatly interfering with superficial flows (O'Driscroll et al. 2010; Wałęga et al. 2015). The natural water cycle, such as rainfall interception, infiltration and evaporation, was unsettled by urbanization, which caused a series of urban flood management issues, e.g. frequent flooding, water environment deterioration and serious water shortages (Tan et al. 2014). When the watertightness of a basin is increased, infiltration and evapotranspiration are limited, leading to a decrease in the groundwater level. In turn, sewage systems, which are adapted to quickly carry away rainwater from the drained basins, may contribute to the rise of flow concentration in receiving bodies of surface water during excessive rainfall events. Huge amounts of rainfall water, which occur during thawing and excessive rainfall events, overload the hydraulics of classic rainfall sewage systems, consequently leading to local damage within the basin area. To prevent such damage, semi-natural devices are increasingly being used to alleviate problems during excessive rainfall events (Boancă et al. 2018; Wałęga et al. 2018). Such systems are grouped in the category of low-impact development (LID) or best management practices (BMPs) (Ahiablame et al. 2013). The treatment practices have been identified as sustainable methods of managing stormwater, e.g., by temporary retention and subsequent introduction into the ground by infiltration. These solutions are often considered "best management practices" (Fletcher et al. 2015; Wałęga, Wachulec 2018). The "sponge city" is a new concept that can help to increase the protection of a city against storm floods (Dong et al. 2019). This concept is based on green/gray stormwater infrastructure (Li et al. 2018); through different protection and planning strategies for these areas, the integration and connectivity of the ecological sources can be improved, resulting in a higher urban ecological security (Dong et al. 2019). The efficiency of these devices depends on local hydrogeological conditions such as ground permeability, the condition of ground water levels and meteorological conditions, such as precipitation and potential evaporation.

The aim of this research was to determine the influences of meteorological and hydrogeological factors on the changes in water levels in a rainwater storage and infiltration reservoir.

2. DESCRIPTION OF THE EXAMINED RESERVOIR

The examined reservoir is located in the urban and industrial area of Krakow (małopolskie voivodeship), on ground owned by the Polish State Railways (PKP), Kraków-Bieżanów branch, on the left side of the railway embankment of the Mydlniki-Gaj route, near the viaduct over the Półłanki St. (Fig. 1).

The location, shape and size of the reservoir are determined by the railway track embankment in the north-west, by Złocieniowa St. in the north-east, by Półłanki St. in the north and by uncultivated land covered with bushes and single trees in the south-west. The drained basin mostly has the features of an urbanized basin, which is characterized by the occurrence of impervious surfaces, namely asphalt roads, pavements, rails, railway switches and surfaces under buildings.

The land in the vicinity of the reservoir consists of grasslands, uncultivated grounds covered with bushes and fields for vegetable cultivation. There is no surface water drain in the analyzed area. In the drained area, there are sub-basins with diverse coefficients of surface runoff (Table 1).

The geology of the area, where the storage and infiltration reservoir is located, is the southern edge section of the high fluvial terrace of the Vistula River. Underneath the surface, there is a layer of semi-permeable Holocene and Quaternary Vistula silts with a high content of organic substances and a thickness of a few meters.

There are layers of Pleistocene and fluvioglacial sands and gravel of the glaciation period in the south of Poland, descending to a depth of 10 to 20 m. The stratum for quaternary formations is formed by Neogene, Tertiary, and grabowieckie layers consisting of silts and sands. On the basis of the expert geological opinion issued by BP and RBK in Kraków, it was stated that the water table is at a depth of approximately 2.9 m below the surface. According to boreholes in the area, down to a depth of 4.5 m, there are sand layers with a filtration coefficient to the value of k_f = 8.6 m·d^{-1} (9.95·10^{-5} m·s^{-1}). The given filtration coefficient was determined on the basis of the granulometric composition of the ground.

As there is electricity running along the water table, the contractor left a 0.5-m thick layer (measured from the reservoir bottom) of cohesive soil, with a filtration coefficient of k_f = 0.0086 m·d^{-1} (9.90·10^{-8} m·s^{-1}) to balance the pressure of the groundwater head. Grain size analysis of the reservoir bed confirmed the previous predictions concerning permeability.

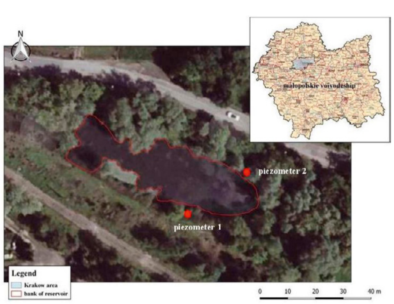

Fig. 1. Location of the storage and infiltration reservoir

Table 1. The areas of sub-basins the urban and industrial area of Krakow with their corresponding coefficients of surface runoff (Krzanowski, Radecki-Pawlik 1998)

Land cover	Watershed area [km^2]	Coefficient of surface runoff [-]
Uncultivated ground and vegetable fields	0.387	0.150
Railway areas	0.058	0.300
Roads, car parks, etc.	0.005	0.700
All	0.450	0.175*

* – mean value of surface-runoff coefficient

In accordance with the modified Pruszyński method, aerometric analysis demonstrated the occurrence of cohesive soil at the bottom of the reservoir, the grain-size distribution of which corresponds with silty clay loams. The granulometric composition of the ground at the bottom of the reservoir is also affected by deposits from excess (unleached) rainwater.

The reservoir complex consists of the following devices for water intake, transport, storage and the treatment of rainwater coming in from the basin:

- Two concrete reduction chambers with sedimentation tanks, located in ditches of the railway viaduct along Półłanki St., with 3×400-mm pipelines connecting the chambers;
- An open channel with a length of 63 m and a bottom width of 0.4 m, laid at a slope of 2% and reinforced with prefabricated concrete slabs, taking water from the reduction chambers to the reservoir, secured at the outlet with a rip-rap to absorb the energy of the excess rainwater entering the reservoir;
- A storage and infiltration reservoir with a bottom area of 1,605 m^2 and a maximum capacity of 1,951 m^3;
- Two piezometers.

The examined reservoir is an earthen structure in the shape of a wedge, narrower at the inlet part (width B_1 = 15.0 m) than the wider section (B_2 = 19.0 m). The length of the reservoir along the side of Złocieniowa St. is 78.8 m, and at the side of the railway embankment, it is 82.5 m. The reservoir bank slope is 1:1.5, and the reservoir inlet has a slope of 1:3; its average depth is 1.50 m, and the bottom slope is 2% in the direction from the inlet towards the reservoir.

To discourage trespassing, the reservoir was fenced. Two piezometers, which were installed at a depth of 1 m below the level of the groundwater table (the ordinate of the bottom of the piezometer is 197.50 m above sea level, and the level of filter is about 1 m) are used to monitor the quality of the stored unleached rainwater, the fluctuation of the groundwater table, and the purity of groundwater in the immediate vicinity of the reservoir.

3. RESEARCH METHODOLOGY

As water runoff from the examined reservoir takes place during infiltration to the ground, it was assumed that the water depth regime in the reservoir is determined by the groundwater table level. One of the main functions of the analyzed structure is the storage of water after storms or long periods of rainfall. For this reason, this meteorological factor should significantly affect the water level in the reservoir and the speed at which the reservoir empties. Evaporation from the water surface constitutes another important factor affecting the water depth oscillations in reservoirs with standing water. The evaporation magnitude depends on several factors, such as water vapor pressure, moisture shortage, air temperature, wind speed, as well as the shape and dimension of the reservoir (Jurak 1976; Bac, Rojek 1979; Atlas 1986; Breitschneider et al. 1993; Jaworski 1997). In his sense, the analysis of a range of climatic and hydrological factors and their inter-relationships can help to determine their influences on the water depth regime in the storage and infiltration reservoir.

Water depth in the reservoir was read from the installed water stage rod. The oscillations of the reservoir water depth were observed from September 2003 to November 2004. First, readings were taken once a week, and when the measurements of potential evaporation started (21/05/2004), readings were taken three times a week.

The groundwater table level was measured from January 2003 to November 2004 at piezometers above and below the reservoir, using a hydrogeological whistle. From January 2003 to May 21, 2004, the level of the groundwater table was measured once a week, and subsequently, towards the end of the measuring period, it was measured three times a week.

Precipitation data were obtained from the meteorological station in the village of Koźmice Wielkie near Wieliczka, taken from January 2003 to November 2004. To obtain the full characteristics of the precipitation near the examined reservoir, a Hellmann rain gauge was installed on June 2, 2004. The depth of the precipitation was read from this gauge as the sum of precipitation in the periods between consecutive readings of water depth in the examined reservoir. To obtain the values of the precipitation depth from the period prior to the Hellmann rain gauge installation, a regression equation was calculated, which describes the depth of the precipitation at the meteorological station as a function of the depth of the precipitation from Koźmice:

$$P_{Bieżanów} = 0.726 \cdot P_{Koźmice} + 1.322 \qquad (1)$$

The obtained correlation coefficient of the value of 0.616 was statistically significant at the level of $\alpha = 0.01$ ($r_{obl} = 0.616 > r_{kr(55;0.01)} = 0.339$).

Potential evaporation was determined via a Piche evaporimeter, which was installed near the reservoir on May 18, 2004, calculated on the basis of values from the periods between the readings from the water stage rod. Air temperature was measured simultaneously with the evaporation rate.

The verification of data used in the model was based on the examination of genetic and statistical homogeneity. In the case of homogeneous data, constant factors affect the process of the given phenomenon (Ozga-Zieliński 1987; Ozga-Zielińska, Brzeziński 1997). As the test results show, the change of the water depth in the reservoir has various origins. In the case of thawing, a slow increase in water depth is observed in the reservoir. However, when short-term rainfall from storms occurs, the reservoir fills up quickly, and the water level gradually falls. A similar situation occurs in the case of variability of the first level of groundwater.

Chełmicki (1991) shows that the water table is mainly fed during the thawing period, whereas in the summer period, despite the occurrence of heavy storms, the level of groundwater does not change significantly. The described relationships show a lack of genetic homogeneity in the case of water depth changeability in storage and infiltration reservoirs and the groundwater table. The remaining variables are determined by constant factors; thus, it can be assumed that the changeability of potential evaporation and the depth of precipitation have the same origin. To confirm these assumptions, a statistical homogeneity test was performed for each independent and dependent variable. The analysis was performed by means of a Kruskal-Wallis rank sum test. In this test, the elements of samples originating from one general population are given ranks; the sum of ranks is then determined, and the importance of the differences of these sums is checked by a χ^2 test. The list of the results of statistical homogeneity of variables for which the analysis was performed is shown in Table 2. The performed calculations show that in the case of the water depth in the reservoir and the conditions of the groundwater table, the obtained data are statistically heterogenous. These results confirm that various, changeable-over-time factors affect the course of these phenomena.

Chełmicki (1991), in tests on the regime of the shallow groundwater table in Poland, shows that about 35% of measuring stations lack statistical homogeneity. The significantly ascending trend of the water table was, most likely, caused by the lack of data homogeneity.

Heterogenous variables were used in further analyses as they have a decisive influence on the operation of the reservoir. The strong mutual connection between the heterogeneous variables supports their use in further analyses. The interconnections between the selected factors were determined on the basis of the analysis of simple and partial correlations. The importance of the correlation coefficients was established by means of the comparison of their values with the critical values read in the statistical tables at the given significance level α and n degrees of freedom.

Table 2. Results of the Kruskal-Wallis test of variable homogeneity

Variables	χ^2 value	Analysis results
Water depth in the reservoir [m]	18.831	Heterogenous
Groundwater table level ground water table [m under the ground level]	16.179	Heterogenous
		Homogeneous
Potential evaporation [mm]	1.417	Homogeneous
Depth of precipitation [mm]	3.175	

Table 3. Statistical characteristics of the analyzed variables in the storage and infiltration reservoir in the urban and industrial area of Kraków

Variable	Mean [m]*	Minimum [m]*	Maximum [m]*	Standard deviation [m]*	Coefficient of variation [–]	Amplitude [m]*
Reservoir	0.385	0.140	0.780	0.193	0.501	0.640
Piezometer 1	1.890	0.735	2.430	0.374	0.198	1.690
Piezometer 2	2.930	1.600	3.525	0.460	0.157	1.925
Potential evapotranspiration	3.820	0.060	8.100	2.354	0.616	8.040
Precipitation	8.460	0.00	64.00	11.040	1.305	64.000

* for potential evapotranspiration and precipitation values are in mm

4. TEST RESULTS AND DISCUSSION

The basic characteristics of the analyzed factors are shown in Table 3, and their variability in the test period is shown in Figures 2a-d.

From the beginning of the tests (13/09/2003) until the end of 2004, the water depth in the reservoir decreased gradually (Fig. 2a), which resulted in the lack of water supply in autumn due to low precipitation. A visible fall in the depth of precipitation in this period was identified (Fig. 2c). Occasional precipitation (14.5 mm) did not cause any visible changes in the reservoir level. A significant increase in the reservoir water depth was preceded by a larger precipitation in the given period of time and increased air temperature, which then caused thawing and meltwater influx. The maximum influx to the reservoir was recorded on 19/04/2004, with a value of 0.78 m (Table 3, Fig. 2a). A significant rise of the groundwater table, recorded on piezometer 2, also had an influence on the water depth (Fig. 2b).

The spring-summer period was characterized by a gradual, even decrease in reservoir water depth until it reached its minimum value of 0.305 m on 26/07/2004. This decrease resulted from the gradual reduction of rainfall. In this period, the sum of precipitation, calculated for the period between the consecutive readings of water depth in the reservoir, exceeded 20 mm by six times. The decrease in water depth in the reservoir is connected with the increase in the level of the groundwater table, and consequently, the hydraulic gradient and the efficiency of the infiltration water stream connected with it increased. Another significant increase in reservoir water depth was caused by the 3-day record amount of precipitation from July 28 to 30, 2004, reaching a value of 64 mm and resulting in an intense run-off feeding of the reservoir, causing a water depth of 0.525 m on August 2, 2004. A further increase in water depth was also caused by rainfall, albeit to a lower degree. This is because each consecutive rainfall event fell on saturated ground, and thus, its ability to be absorbed into the ground was limited, which is also proved by the increase in the groundwater table near the reservoir. The second visible maximum fill-up of the reservoir to a value of 0.605 m was recorded on August 9, 2004. After this period, the water depth again decreased to a minimum value of 0.205 m on October 4, 2004.

The regime of the water table in the reservoir depends on the supply of rainwater and the extent of infiltration. Swelling was caused by thawing run-off during the spring period from March 3 to April 19, 2004, and during extreme rainfall events during summer from July 26 to August 9, 2004. The amplitude of the water depth in the reservoir was 0.64 m(0.78 – 0.14 = 0.64 m; Table 3). The average water depth in the reservoir during the experimental period was 0.385 m.

After the period of water level increase from the end of March until July 26, 2004, the groundwater table fell to a value of 3.03 m below ground level. This was a period of sparser precipitation and intense ground evaporation, leading to a decrease in the groundwater table. This decrease was also caused by a reduced supply of water infiltrating from the reservoir to the groundwater table. It is worth noting that the groundwater table rose again in the period from July 26 to August 2, reaching a value of 2.295 m below ground level. This increase was caused by extreme rainfall events in this period, with a total rain amount of 87.1 mm, accounting for more than 9.8% of the total rainfall in the experimental period.

After a secondary increase in the groundwater table level recorded by piezometer 2, a decrease was observed until October 10, 2004, when the level reached 3.21 m below the ground level. Su sequently, the level has stabilized at 3.209 m below ground level. The third increase in the groundwater table level was observed from November 9 to 20, 2004, reaching 2.08 m below the ground level.

The influence of the storage and infiltration reservoir on the groundwater table regime is presented in Figure 3a and 3b. The terrain topography impacts the level of the groundwater table, which was measured by piezometer 1, making it higher than the level measured in the reservoir (Fig. 3a). This proves that during the entire experimental period, groundwater infiltrated into the reservoir. The opposite situation occurred below the reservoir (Fig. 3b). Because for most of the experimental period, the level of the water table in the reservoir was higher than the groundwater level, water infiltrated from the reservoir to the groundwater system.

During the entire experimental period, groundwater reached the reservoir only in two cases, on March 24 and 30, 2004. During these times, the groundwater level decreased more rapidly because of water infiltration from thawing and rainfall than the reservoir water level increased. The slower increase of the water level in the reservoir was the result of the slower surface run-off from the basin into the reduction chambers and inlet channel. It must also be stressed that, because the ground layer of the reservoir has

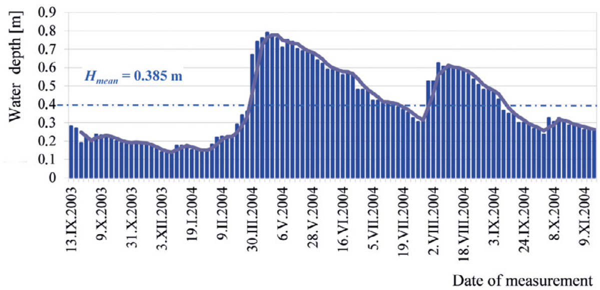

Fig. 2a. Water depth in the storage and infiltration reservoir in the urban and industrial area of Kraków in the experimental period

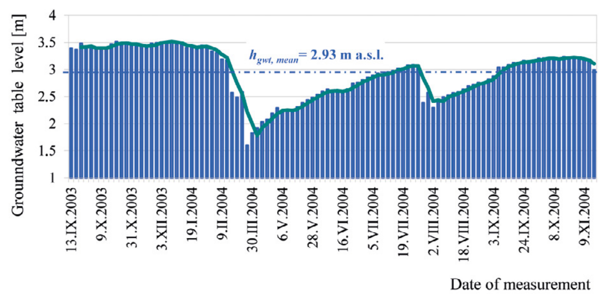

Fig. 2b. Levels of groundwater table in piezometer 2 in the storage and infiltration reservoir in the urban and industrial area of Kraków

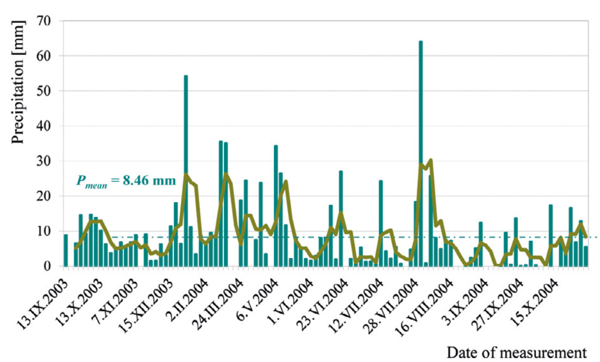

Fig. 2c. Depth of precipitation in the test period in the immediate vicinity of the storage and infiltration reservoir in the urban and industrial area of Kraków reservoir

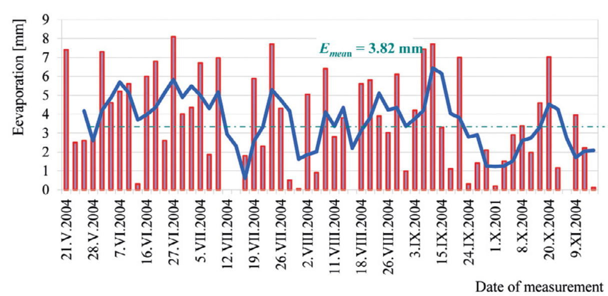

Fig. 2d. Level of the potential evaporation in the examined period in the vicinity of the storage and infiltration reservoir in the urban and industrial area of Kraków; the solid line represents the consecutive mean of three consecutive values

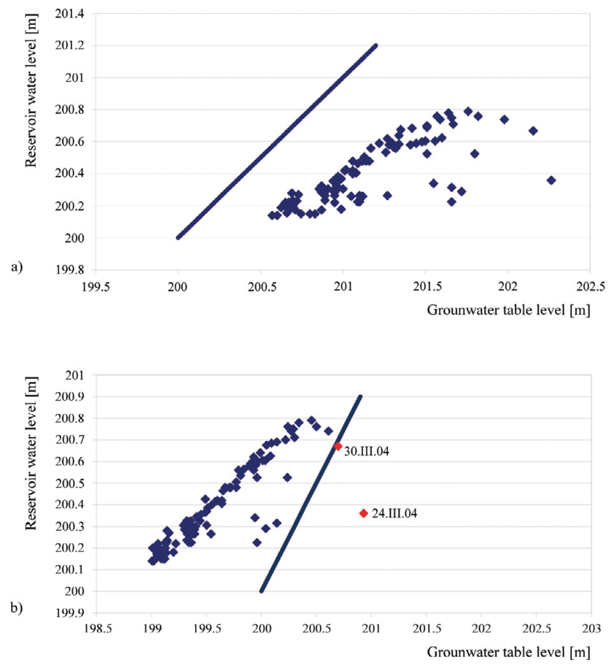

Fig. 3. Relationship between reservoir water level and groundwater table level at piezometer 1 (a) and piezometer 2 (b); the horizontal line represents the situation when the ordinates of the water table in the reservoir are equal to the ordinates of the groundwater table

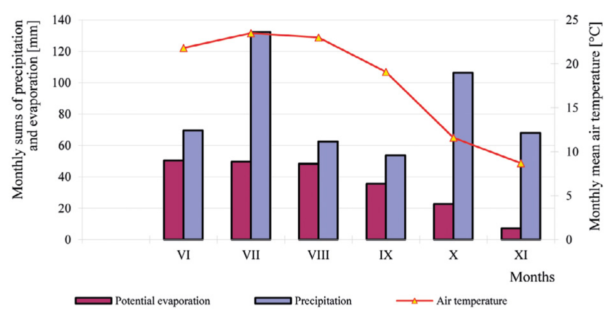

Fig. 4. Monthly sums of potential evaporation and depth of precipitation against the mean monthly air temperature values in close vicinity of the reservoir

Table 4. Matrix of correlation coefficients for the analyzed variables

Parameter	H_{res}	H_{gwt}	ΣP_{i-1}	ΣE_p
H_{res}	1.000	−0.950	0.420	0.510
H_{gwt}	−0.950	1.000	−0.410	−0.450
ΣP_{i-1}	0.420	−0.410	1.000	0.190
ΣE_p	0.460	−0.450	0.190	1.000

H_{res} – water depth in the reservoir; h_{gwt} – level of groundwater table at piezometer 2; ΣP_{i-1} – sum of precipitation from the week before the measurement of water depth in the reservoir; ΣE_p – weekly sum of potential evaporation a thickness of around 0.50 m and a poor permeability (silty clay loams), the levels of the reservoir and the groundwater are related. When the level of the groundwater table is close to the reservoir bed, there is a direct relationship between them, and the groundwater is in direct hydraulic contact with the water in the reservoir; the reservoir is then fed with groundwater. When the level of the groundwater table is below the reservoir bed, these relationships are not direct. The water in the reservoir does not have direct contact with the groundwater, and evaporation from the water surface, evapotranspiration, and precipitation become the more significant factors.

Throughout the entire experimental period from September 13, 2003, to November 20, 2004, the sum of precipitation was 772 mm. Precipitation characteristics of this period were determined on the basis of the classification by Kaczorowska (1962). The depth of normal precipitation in the period from 1850 to 1997, measured by the weather station at the Botanical Garden of Jagiellonian University in Krakow, was 672 mm (Twardosz 1999). Taking into account this measurement, the analyzed period in the Krakow-Bieżanów region can be regarded as being wet (with the precipitation sum being 12.9% higher than the normal precipitation). Twardosz also writes that in the period from 1850 to 1997, there were 26 wet years.

Potential evaporation fluctuated significantly (Fig. 2d), partly because of the different time spans between successive readings. The maximum sum of evaporation in the experimental period was 8.1 mm, recorded from June 23 to 27, 2004. The highest value of evaporation was 0.06 mm, recorded from July 28 to 30, 2004. (Table 3). Mean evaporation throughout the experimental period was 3.81 mm, with an evaporation sum of 229.2 mm.

In the entire experimental period, the supply of water from precipitation was higher than water loss from evaporation. This was most obvious in July and October, which had the highest values of precipitation sum (Fig. 4). In July, the sum of precipitation was 132.4 mm, while water loss through evaporation was 49.6 mm. In months with relatively high values of air temperature and lower values of precipitation, the proportions of these two parameters were more equal. Such a situation occurred in August and September; the sum of precipitation in these months was 62.6 and 53.8 mm, respectively, with mean temperatures of 23 and 19.1°C, resulting in evaporation values of 48.3 and 35.5 mm, respectively. The evaporation level was 77% of the precipitation level in August and 66% of that in September. By comparison, evaporation was only 37.5% of the depth of precipitation in July.

The vital issue for a designer or user of a seminatural structure is the ability to forecast its functioning, particularly with regard to its filling. To identify factors that affect the depth in the examined reservoir, linear correlation analysis was used. For the weekly mean depth of the groundwater table measured using piezometer 2, the independent variables were the sum of precipitation from the week before and the weekly sum of potential evaporation.

In the performed analysis, the value of precipitation and the value of depth read from the water stage rod 1 week before were taken into account because of the delayed reaction of the reservoir to the precipitation which resulted from the diverse influence of physiographic parameters, especially the shape and the slope of the basin, the use and the characteristics of precipitation, its intensity, its depth, and its duration [Banasik, Barszcz 2000]. The reduction chambers holding the first waves of the run-off also have an effect on the abovementioned delay.

Based on the analysis of the calculations of the correlation between the dependent variable (reservoir water depth) and the other independent variables (Table 4), these depths are mostly connected with the levels of the groundwater table. The calculated correlation coefficient of the value of $r = -0.95$ is statistically significant at the level $\alpha = 0.01$ for $N = 25$ ($r = -0.95 > 0.487$). Such a strong relationship can be explained by the decrease of the hydraulic gradient with increasing groundwater table levels, leading to a decreased filtration efficiency. As a consequence, the run-off by means of the infiltration from the reservoir decreases. This may be the result of the difficulties of water from excessive rainfall filtering through the ground, which is already saturated with water, and the base of the reservoir is sealed. For this reason, most of the rainfall water runs into the reservoir, thus filling it up. In the case of smaller values of precipitation sum in autumn-winter and early spring, the reservoir is supplied with water coming mainly from thawing. This causes the filling of the reservoir and the rise of the groundwater table as a result of the filtration of meltwater to the ground. Our analysis showed a statistically significant relationship between the depth of the water in the reservoir and the sum of the precipitation from the week before the measurement of reservoir filling. The calculated correlation coefficient had a value of 0.42 and was statistically valid at the level of $\alpha = 0.05$. This significant relationship is caused by the previously described delayed reaction of the reservoir to the surface run-off. When precipitation increases, especially during excessive rainfall events, the filling of the reservoir increases as a consequence of the higher intensity of inflow than run-off via infiltration and evaporation.

A similar situation to that described above occurs when there is a correlation between the water depth in the reservoir and the level of potential evaporation. The values of potential evaporation, which were used in the calculations, were obtained from the period from the end of May to the end of November. The level of evaporation increased, consequently causing a decrease of the water depth in the reservoir, especially in the period from June to August with high air temperatures. However, the calculated correlation coefficient (0.5) between the water depth in the reservoir and the weekly sum of evaporation seems to contradict the previous statement, most likely because the highest levels of evaporation occurred in the period of the most intense precipitation in the summer months. Thus, the higher rainfall increased the reservoir water depth, which did not decrease afterwards due to a relatively small surface and a smaller thermal potential, despite intense evaporation.

5. CONCLUSIONS

Our results led to the following conclusions:

1. The lowest water level was observed in the autumn and winter period as a consequence of a lack of rainfall and a lack of snow and ice thawing. The increase of the water table level in the reservoir is connected with the increase of the groundwater level and it is observed in the spring and summer periods, when there is a high supply of meltwater and stormwater. The average water level in the reservoir was 0.385 m, with an amplitude of 0.64 m.
2. In the period from the beginning of February to the end of March, the groundwater table increases as a consequence of thawing, and the groundwater system is fed by filtrating

meltwater. A secondary increase in the groundwater table level can be observed at the end of July, caused by excessive rainfall events.

3. Throughout the entire experimental period, the reservoir was fed by infiltering groundwater from the area of the basin located above the reservoir. However, the reverse situation took place in the section located below the reservoir. For most of the experimental period, the water infiltered from the reservoir, and the groundwater level increased. The exception is the period from the end of March, when groundwater infiltrated into the reservoir as a result of the increased feeding of the water-bearing stratum with meltwater and significant rainfall, with an almost empty reservoir after the autumn and winter periods.
4. The weekly water depth averages in the reservoir are closely correlated with all variables analyzed here, namely average levels of groundwater table below the reservoir in the given week, sum of precipitation from the week prior to the date of the examination of water depth in the reservoir, sum of potential evaporation in the given week. However, the water depth in the reservoir is most significantly connected with the level of the groundwater table. Meteorological factors, such as the sum of precipitation and evaporation, have an influence on the statistically valid relationship between the weekly water depth averages in the reservoir and the corresponding levels of the groundwater table. Because the experiments were performed within a relatively short time, with high sums of annual precipitation, the results are valid only for wet years. For dry or normal years, the relationships between water level in reservoir, sum of precipitation and evaporation, and groundwater levels may be slightly different. For example, for example for normal and dry years, infiltration water from the reservoir may be dominant in both piezometers.
5. Knowledge of all factors affecting the performance of semi-natural rainwater purification plants will help to forecast their operation under various meteorological and hydrogeological conditions, thereby supporting the determination of their impacts on adjacent areas.

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Flow descriptors for parametric hydrographs accounting for afforestation of the catchment

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ABSTRACT. Parametric flow hydrographs are used for design and management purposes in such fields as water management and aquatic engineering. They describe a theoretical hydrograph based on such parameters as maximum flow, time to peak, and surge duration. They are used to forecast flood risk and to evaluate the impact of land use on the run-off hydrograph. In Western Europe for many years methods have been used in which parametric hydrographs are determined based on physical catchment descriptors (PCDs), which are divided into three groups describing the physical features of a catchment. These descriptors are used to derive formulae enabling the determination of parametric flow hydrographs for any computational cross-section. In this work, such formulae are derived for the catchment of the Raba River, using the principles of design hydrology applied in Western European countries. The parametric hydrograph is described using Baptista's gamma density function. The input hydrograph was a nonparametric flow hydrograph determined by Archer's method. For nine gauging stations located in the Raba catchment, physical catchment descriptors were obtained for two 30-year periods: 1961-1990 and 1983-2012. Based on the nonparametric flow hydrograph and the PCDs, two groups of formulae were derived to describe the parametric hydrograph. Analysis of agreement between the computed parametric flow hydrographs and the input hydrograph indicated a high quality of fit. It should be noted that the formulae and analysis presented here refer only to the Raba catchment. However, the results confirm the possibility of applying these methods to the determination of parametric flow hydrographs for any river cross-section.

KEYWORDS: hysical catchment descriptors, gamma density function, parametric flow hydrograph, Archer's method, skewness coefficient, hydrograph width.

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1. INTRODUCTION

Parametric hydrographs are used in water and wastewater management and spatial planning, as well as in aquatic and hydraulic engineering, in cases where variation of the flow in a watercourse plays an important role in the design or computational process (O'Connor et al. 2014). Flow hydrographs describe the theoretical course of a surge, using such parameters as maximum flow, time to peak, and surge duration. Hydrographs of this type are also used in assessing the impact of urbanised areas on flood risk, or the impact of afforestation in ameliorating the effects of floods. The method is used in relation to both existing land use and planned developments in river catchment areas. Hydrographs are also used in planning the capacity of storage reservoirs, one of the purposes of which is to reduce the effects of floods and water shortages at times of drought (Mioduszewski 2012, 2014).

The history of the use of flow hydrographs goes back to the 1930s. It is generally considered that the theory of isochrones developed by Dubelir, Boldakov, and Čerkašin initiated the development of hydrographs of this type for practical engineering purposes. That theory is based on a generic equation of a flood crest. Until the mid-1960s this equation was solved with the use of simplifications, which produced hydrographs of trapezoidal or triangular shape (Strupczewski 1964; Strupczewski et al. 2013).

The first analytical description of a hydrograph was provided by the functions proposed by Reitz and Kreps (Reitz, Kreps 1945; Gądek, Środula 2014). In that method, the rising limb of the hydrograph of the Reitz-Kreps equation is a squared sine function, and the recession limb is an exponential function. The method is still in use today.

An important date is 1957, when Nash's cascade model was introduced for what is called the Instantaneous Unit Hydrograph (IUH) (Nash 1957). In many countries, the gamma density function used by Nash in that model has become the basis for the description of an analytical hydrograph, known as a parametric design hydrograph.

In this work we propose the introduction in Poland of new principles for the construction of empirical formulae, as used in Western European countries, among others, for design hydrology. These formulae enable the determination of parametric flow hydrographs based on:

- the hydrograph width (hours) at 50% and 75% of peak flow ($W50$ and $W75$) and the hydrograph skewness coefficient s;
- the shape parameter of the hydrograph n and the time to peak t_p of the gamma distribution function.

An innovative feature of this method is the ability to determine parametric flow hydrographs for any river cross-section based on equations constructed using the above parameters.

The proposed method is analysed in the catchment of the Raba River, where nine gauging stations are situated. For the data from these stations, an assessment is made of the agreement between the parametric flow hydrographs and nonparametric hydrographs obtained by Archer's method.

2. MATERIALS AND METHODS

The proposed method of determining a parametric design hydrograph using physical catchment descriptors (PCDs) is based on design hydrology. This term, used in European countries and in the United States, denotes a form of hydrology distinct from the existing engineering hydrology in that it combines the computational methods recommended in engineering hydrology with dynamic (process) hydrology, and makes use of data acquisition, data processing, and presentation of results in a GIS. The technique has been developed for such purposes as the management of water resources, the designation of zones endangered by or at risk of flood, assessment of the impact of urbanised areas on flood risk and drought, and determination of the effects of climate change on water resources.

A principle of design hydrology is the use of universal computational methods over large areas, which means that at every level of management it is possible to perform various types of hydrological analyses, in view of the simplicity of using system and the lack of ambiguity in the computed hydrological characteristics.

The parameters used in the computational formulae are called physical catchment descriptors (PCDs). These can be divided into three groups:

- fixed: related to the topography, orography, and hydrography of the catchment, including, e.g., the area of the catchment, the density of the river network, gradient of the river, etc.;
- variable: representing the spatial development of the basin, e.g., forest cover, urbanisation, length of watercourses subjected to anthropogenic pressure, etc.;
- process-related: e.g., moisture content of the catchment, surface retention, channel and lake dampening, urbanisation pressure on the outflow, etc.

In Poland, the methods employed to date use hypothetical waves, determined based on what are known as typical hydrographs, for example, with the highest recorded flow or the highest values of, say, six or eight surges in a selected period. These methods include Reitz and Kreps (1945), Warsaw University of Technology (Gądek et al. 2016), Hydroprojekt (Gądek, Środula 2014) and Cracow (Gądek, Tokarczyk 2015; Gądek et al. 2016). They also include Strupczewski's analytic wave (Ciepielowski 1987, 2001; Strupczewski et al. 2013; Gądek et al. 2017b).

The parametric design hydrographs proposed in design hydrology can be determined in any desired river cross-sections irrespective of catchment size, thanks to a method developed by Archer. This method entails the determination of nonparametric hydrographs – that is, a median of flow hydrographs – and their use to determine flow duration descriptors with probabilities of being exceeded ranging from 95% to 5% in steps of 5%. The value of the 98% flow duration descriptor is also determined (Archer et al. 2000). A nonparametric hydrograph has an independent rising limb and an independent recession limb (Fig. 1). Flows are presented in the form of percentage contribution in a range from 0% to 100%, where 100% denotes the maximum value. The horizontal axis is the duration of particular values of percentage contributions together with higher values. The time is given as negative values for the rising limb of the hydrograph, and positive values for the recession limb. At time $t = 0$ the maximum percentage contribution ($q = 100\%$) occurs. For particular values of percentage contributions of flows, the time is determined in the form of a median, separately for the rising limb and for the recession limb (O'Connor, Goswami 2009; O'Connor et al. 2014; Gądek et al. 2017a, b). Such a nonparametric hydrograph ought to be determined based on a 30-year series of flow data used in the process of computing maximum flows with a given probability of being exceeded.

In the case of hypothetical waves, hydrographs were determined based on time criteria, while in the case of nonparametric Archer hydrographs, time is determined based on unified flow.

For the description of a parametric design hydrograph the gamma density function is used, based on:

- the single shape parameter *m* (O'Connor et al. 2014; Strupczewski 1964; Strupczewski et al. 2013);
- the single shape parameter *n* (Baptista 1990; Baptista, Michel 1990);
- or the two shape parameters *m* and *n* (Strupczewski 1964; Strupczewski et al. 2013; Gądek et al. 2017b).

The basic formula for the gamma density function with two wave shape parameters has the form:

$$q_t = \left(1+\frac{t}{t_p}\right)^m \exp\left\{\frac{m}{n}\left[1-\left(1+\frac{t}{t_p}\right)^n\right]\right\} 100\% \quad (1)$$

where: q_t is the percentage of peak flow at time t [%]; t_p is the time to peak [h]; t is the time from the beginning of the rising limb [h]; m, n are unitless shape parameters.

A function proposed by Baptista is similar in form, derived based on a hydrological model of transformation in the channel of the Muskingum River:

$$q_t = \left(1+\frac{t}{t_p}\right)^2 \exp\left\{\frac{2}{n}\left[1-\left(1+\frac{t}{t_p}\right)^n\right]\right\} 100\% \quad (2)$$

As a result of our analyses, the single-parameter distribution proposed by Baptista was selected.

2.1. STUDY AREA

The study area was the catchment of the Raba River, which flows through three hydrological regions. The largest part of the catchment lies in the mountainous Carpathian zone. The average elevation in the catchment is approximately 500 metres above sea level; the highest point is Mount Turbacz (1,310 m a.s.l.) and the lowest is the river's confluence with the Vistula at 180 m a.s.l. The river may be divided into three sections:

- the upper section, in the Beskid Mountains, 60 km long, with average slope 0.85%;
- the middle section, in the foothill region, 34 km long with average slope 0.23%;
- the lower section, in the Sandomierz Basin, 43 km long with average slope 0.06%.

Within the catchment there are nine gauging stations and a barrier reservoir in Dobczyce. Figure 2 shows the subcatchments for the gauged cross-sections for which computations were performed. The Raba catchment was chosen for study because of the dominance of forests in its upper part. The distribution of forests according to the CORINE Land Cover system, from the years 1990 and 2012 (CLC1990, CLC2012[1]), is shown in Figure 3.

Physical catchment descriptors for the Raba catchment were determined at nine gauging stations.

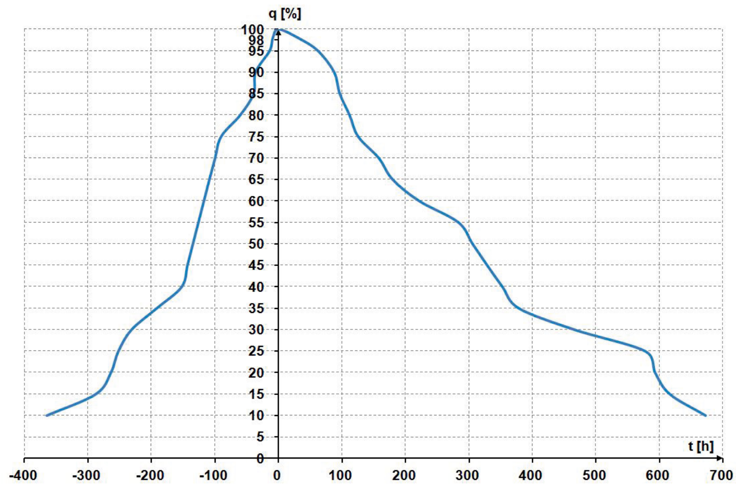

Fig. 1. Example nonparametric design hydrograph obtained by Archer's method

Table 1. Physiographic parameters of the Raba catchment according to the Polish Hydrographic Division (IMGW 1980a)

Parameter	Value
Catchment area	1,537.1 km²
Main river length	131.9 km
River slope	4.47 m/km
Drainage density	2.16 km·km⁻²
River source elevation	780 m a.s.l.
Final confluence elevation	190 m a.s.l.

Table 2. Land cover types of the Raba catchment according to CORINE Land Cover

Cover types	Area [%]	
	1990	2012
Discontinuous urban fabric	1.62	5.71
Industrial or commercial units	0.11	0.20
Mineral extraction sites	0.02	0.06
Green urban areas	0.05	0.02
Sport and leisure facilities	-	0.05
Non-irrigated arable land	30.19	31.91
Fruit trees and berry plantations	0.53	1.35
Pastures	2.62	2.74
Complex cultivation patterns	15.71	9.17
Land principally occupied by agriculture, with significant areas of natural vegetation	16.21	12.57
Broad-leaved forest	4.37	4.45
Coniferous forest	16.96	17.99
Mixed forest	10.81	11.98
Transitional woodland – shrub	0.09	1.05
Water bodies	0.70	0.76

2.2. ANALYTICAL METHODOLOGY

2.2.1. PHYSICAL CATCHMENT DESCRIPTORS

To construct empirical formulae enabling the determination of parametric flow hydrographs, physical catchment descriptors from the three groups were used: the fixed descriptors ADO, GSR, S1085; the variable descriptor LAS (Bayliss 1999); and the process-related descriptors GLEMOK, JEZ.

[1] https://land.copernicus.eu/pan-european/corine-land-cover

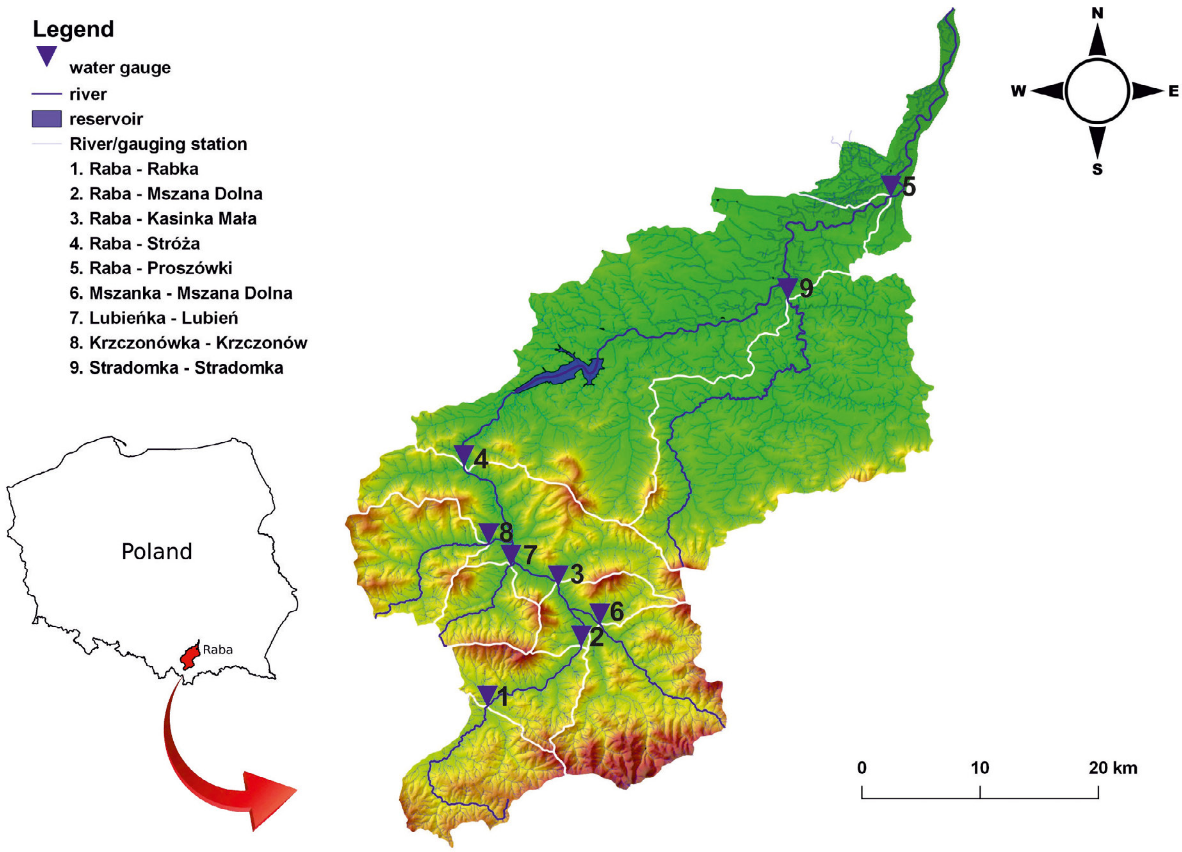

Fig. 2. Gauging stations in the Raba catchment

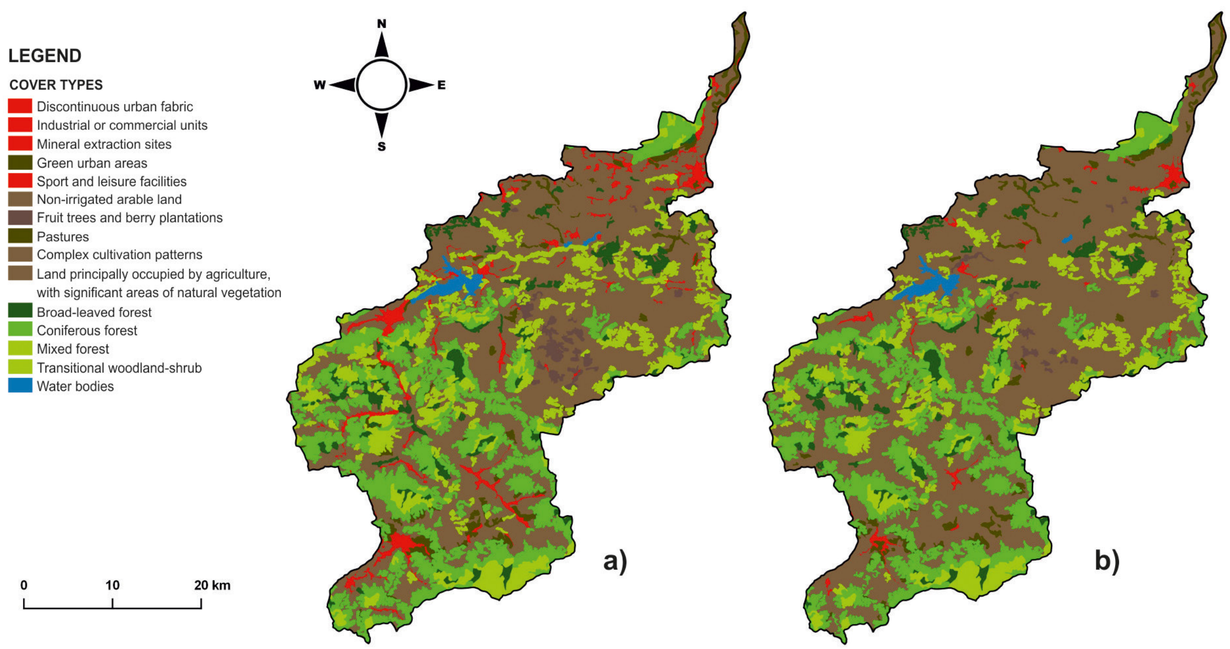

Fig. 3. Land cover of the Raba catchment according to CORINE Land Cover: a) 1990; b) 2012

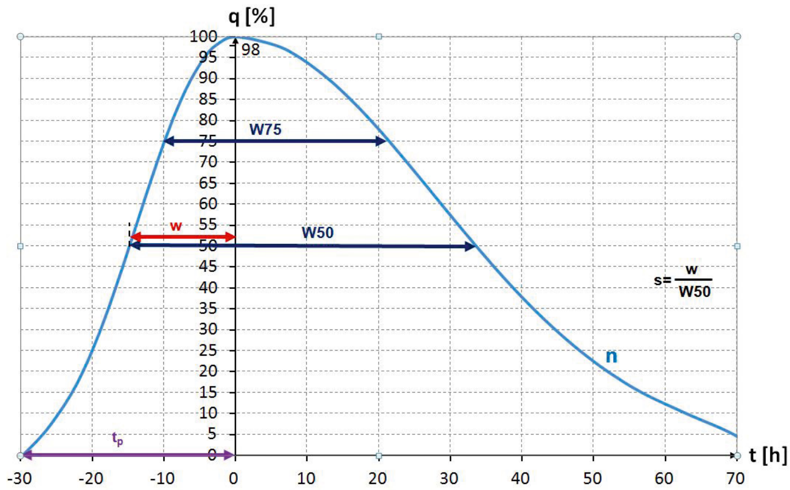

Fig. 4. Example parametric design hydrograph

The ADO descriptor represents the proportion of the area drained directly by tributaries, modelled on the ARTDRAIN descriptor (Bayliss 1999), and given by the formula:

$$ADO = \frac{\sum A_{eli}}{A} \quad (3)$$

where: A_{el} is the area of a subcatchment (over 2.5 km^2) [km^2]; A is the area of the catchment upstream from the gauging station [km^2].

The GSR descriptor represents the drainage density, and is modelled on the DRAIND descriptor (Bayliss 1999) according to the formula:

$$GSR = \frac{\sum L_i}{A} \quad (4)$$

where: L is the length of a watercourse for which the catchment area exceeds 2.5 km^2 [km]; A is the catchment area upstream from the gauging station [km^2].

The S1085 descriptor, representing the slope of the main river (Bayliss 1999), is computed based on the drop in elevation of the river between the theoretical source and the theoretical computational cross-section, and the length of the river between them. The theoretical computational cross-section is located at a distance of 10% of the river length above the computational cross-section. The theoretical source is located at a distance of 85% of the river length above the computational cross-section.

$$S1085 = \frac{W85 - W10}{L1085} \quad (5)$$

where: $W85$ is the elevation of the river at a cross-section located at a distance of 85% of the river length above the computational cross-section [km]; $W10$ is the elevation of the river at a cross-section located at a distance of 10% of the river length above the computational cross-section [km]; $L1085$ is the length of the main river excluding sections of 10% of its length above the computational cross-section and 15% of its length from the source [km].

This slope is used in place of the average slope computed by the Taylor-Schwartz method (Bayliss 1999).

The LAS descriptor, representing the degree of afforestation of the catchment, modelled on the FOREST descriptor (Bayliss 1999), is computed from the formula:

$$LAS = \frac{\sum A_{LASi}}{A} \quad (6)$$

where: A_{LAS} is the area of forest according to CORINE Land Cover [km^2]; A is the area of the catchment up to the gauging station [km^2].

The LAS descriptor was computed in 1990 for the computation period 1961-1990 and in 2012 for the computation period 1983-2012.

The GLEMOK descriptor represents the time during which the soil is wet. It is based on the PROPWET descriptor developed in the UK (Bayliss 1999; Reed 2007) and the FLATWET descriptor used in Ireland (Mills 2009; Mills et al. 2014), modified by the exclusion of the winter period. For Polish conditions, GLEMOK is determined for the 30-year series of measurement data as the net balance of supply (precipitation) and losses (terrain evaporation) for the daily data and the soil types occurring in the catchment. This balance is calculated for the period from 1 April to 31 October of each year – that is, for the growing season. It is assumed that on 1 April the soil is fully saturated. The boundary between wet and dry soil was determined based on the weighted average of the areas covered by particular soil types and the pF curves (Driessen, Konijn 1992) for each soil type. The GLEMOK descriptor was computed in 1990 for the computation period 1961-1990 and in 2012 for the period 1983-2012.

The JEZ descriptor, describing the process of flood attenuation by reservoirs and lakes, is modelled on the FARL descriptor (Bayliss 1999). It is computed from the formula:

$$JEZ = \prod \alpha_i \quad (7)$$

where:

$$\alpha = \left(1 - \sqrt{r}\right)^w$$

$$r = \frac{A_{JEZ}}{a}$$

$$w = \frac{a}{A}$$

A_{JEZ} is the area of the reservoir/lake [km^2]; a is the catchment area up to the cross-section closed by a dam or hydraulic structure [km^2]; A is the catchment area up to the gauging station [km^2].

The descriptors (PCDs) listed above were determined using digital and analogue data obtained from:

- the Polish Hydrographic Division map (mphp)[2];
- CORINE Land Cover (CLC1990, CLC2012);
- the numerical terrain model (NMT)[3];
- the Polish hydrographic division atlas (distribution of soils) (IMGW 1980a, b);
- the Polish hydrological atlas (indices of spatial distribution of precipitation and values of terrain evaporation) (IMGW 1988a, b);
- weather data, including precipitation for the years 1983-2006, from the Stróża station maintained by the Hydrology Group of the Institute of Aquatic Engineering and Water Management at Tadeusz Kościuszko University of Technology, and for the years 2007-2012 from the IMGW-PIB weather station in Dobczyce.

2.2.2. PARAMETRIC DESIGN HYDROGRAPHS

Based on the nonparametric flow hydrograph obtained byArcher's method, a deter-

[2] https://dane.gov.pl
[3] https://www.eea.europa.eu/data-and-maps/data/eu-dem

Table 3. Physical catchment descriptors (PCDs) for gauging stations in the Raba catchment

River/gauging station	*A*	*GSR*	*S*1085	ADO	JEZ	LAS		GLEMOK	
	km^2	km km^{-2}	m km^{-1}			1990	2012	1990	2012
Raba – Rabka	91.7	2.61	8.99	0.58	1.00	0.39	0.45	0.62	0.63
Raba – Mszana Dolna	157.1	2.55	8.59	0.64	1.00	0.38	0.43	0.59	0.58
Raba – Kasinka Mała	352.9	2.38	7.51	0.81	1.00	0.42	0.43	0.59	0.54
Raba – Stróża	643.1	2.15	6.24	0.86	1.00	0.45	0.49	0.55	0.52
Raba – Proszówki	1,470.4	2.00	3.53	0.85	0.95	**0.32***	0.35	**0.53***	0.50
Mszanka – Mszana Dolna	151.4	2.37	16.00	0.31	1.00	0.46	0.47	0.54	0.50
Lubieńka – Lubień	47.8	2.16	7.73	0.55	1.00	**0.44***	0.49	**0.52***	0.50
Krzczonówka – Krzczonów	87.3	1.86	13.82	0.64	1.00	0.48	0.55	0.46	0.44
Stradomka – Stradomka	362.5	1.99	4.67	0.80	1.00	0.25	0.26	0.41	0.39

* Data not used for optimisation due to incompleteness of the (30-year) series of measurement data in the analysed period

Table 4. Hydrograph width *W*50, *W*75, and skewness coefficient s and their relative errors at gauged cross-sections

No	River/gauging station	*W*50		*W*75		*s*		RE_{W50}		RE_{W75}		RE_s	
		1990	2012	1990	2012	1990	2012	1990	2012	1990	2012	1990	2012
1	Raba – Rabka	34.9	32.7	15.8	14.5	0.4	0.4	2.6	8.2	15.2	0.4	1.8	11.6
2	Raba – Mszana Dolna	35.1	32.5	9.4	13	0.5	0.4	6.4	1.6	35.3	0.6	7.8	9.6
3	Raba – Kasinka Mała	36.8	31.6	16.2	13.7	0.4	0.5	7.1	2.1	14.1	6.2	1.5	3.3
4	Raba – Stróża	33.9	33.2	16.2	14.5	0.4	0.4	4	3.3	5.1	14.2	4	2.1
5	Raba – Proszówki		42.6		18.7		0.4		0.8*		0.5*		1.2*
6	Mszanka – Mszana Dolna	31.2	26.8	13.8	11.5	0.5	0.5	3.2	7.3	1	10.8	10.2	2.4
7	Lubieńka – Lubień		33.6		17.5		0.4		1.1		2.2		11.8
8	Krzczonówka – Krzczonów	29.7	27.5	14.9	13.3	0.5	0.5	4.1	2.4	6.6	5.6	2.8	0.9
9	Stradomka – Stradomka	28.4	26.3	14.4	13.3	0.5	0.5	1.9	1.8	5.6	3.8	1.9	0.8

* the error value is affected by the JEZ descriptor, which was not considered in the optimisation due to the absence of impact of the reservoir on eight of the nine gauging stations

mination was made of the values of hydrograph width at 50% (*W*50) and 75% (*W*75) of peak flow. These descriptors were selected based on experience gained by scientists working on design hydrology in Ireland (O'Connor et al. 2014). An additional parameter describing the parametric flow hydrograph is the skewness coefficient *s*. Baptista's gamma density function requires computation of the shape parameter *n* and the time to peak t_p (Fig. 4).

To construct empirical formulae describing the parametric flow hydrograph, an optimisation process was used, taking as the target function the minimum deviation of the sum of squares between the given and computed values, according to the general formula:

$$f = \sum_{i=1}^{k} \sqrt{(x-\hat{x})^2} = \min \qquad (8)$$

where: *k* is the number of gauging stations used in the optimisation process (*i* = 1, 2, 3, ... 9); *x* is the known value of a descriptor (e.g. *W*50) or of another parameter (e.g. t_p); is the sought value of the descriptor (e.g. *W*50) or another parameter (e.g. t_p).

The optimisation process was carried out independently for the descriptors *W*50 and *W*75 and the skewness coefficient *s*, as well as the parameters describing the hydrograph: *n* and t_p.

3. RESULTS

Table 3 gives the values of the descriptors (PCDs) obtained for the gauging stations in the catchment of the Raba River.

The Proszówki station was not considered in the construction of formulae describing the parametric flow hydrograph, because of the flood attenuation provided by the reservoir in Dobczyce.

Based on the determined PCDs, formulae were constructed to enable the computation of any parametric design hydrograph:

$$W75 = 9.92 \frac{(1+LAS)^{1.54}\, GLEMOK^{1.14}}{GSR^{1.68}\, S1085^{0.55} (1+ADO)^{1.40}\, JEZ^{1.93}} \qquad (9)$$

$$W50 = 22.95 \frac{(1+LAS)^{0.70}\, GLEMOK^{0.79}}{GSR^{0.34}\, S1085^{0.21} (1+ADO)^{0.27}\, JEZ^{2.92}} \qquad (10)$$

$$s = 0.14 \frac{GSR^{0.59}\, (1+LAS)^{0.18}}{GLEMOK^{0.91}} \qquad (11)$$

For Baptista's gamma density function, selected for description of the parametric design hydrograph, the following formulae were obtained:

$$n = 1.33 \frac{GSR^{2.53}\, S1085^{0.70}\, (1+ADO)^{0.35}}{(1+LAS)^{3.24}\, GLEMOK^{3.75}\, JEZ^{1.81}} \qquad (12)$$

$$t_p = 25.45 \frac{1.0}{(1+LAS)^{0.92}\, GLEMOK^{0.60}\, (1+ADO)^{0.51}\, JEZ^{4.72}} \qquad (13)$$

Figure 5 shows the parametric flow hydrographs computed based on:

1. the hydrograph width at 50% (*W*50) and at 75% (*W*75) of peak flow and the skewness coefficient *s*, obtained from the nonparametric flow hydrograph obtained by Archer's method;
2. the hydrograph widths *W*50, *W*75 and the skewness coefficient *s* computed from formulae (9), (10) and (11);
3. the parameters *n* and t_p of Baptista's gamma density function computed from formulae (12) and (13).

4. ANALYSIS AND DISCUSSION

Formulae (9), (10) and (11) are basic equations for determining parametric flow hydrographs at any river cross-section. Their accuracy was assessed by comparing hydrographs determined from values of *W*50, *W*75, and *s* from the nonparametric Archer hydrograph, with the hydrographs computed using formulae (9), (10) and (11) or formulae (12) and (13) for eight gauging stations on the Raba River. Table 4 gives the values of the relative error (*RE*) for hydrographs computed at each gauging station for the two periods 1961-1990 (1990) and 1983-2012 (2012).

The relative error of hydrograph width was calculated from the following formula (Chai, Draxler 2014):

$$RE_p = \frac{|W_p - \widehat{W_p}|}{W_p} 100\% \qquad (14)$$

where: RE_p is the relative error of hydrograph width W_p, *p* = 50%, *p* = 75% or skewness co-

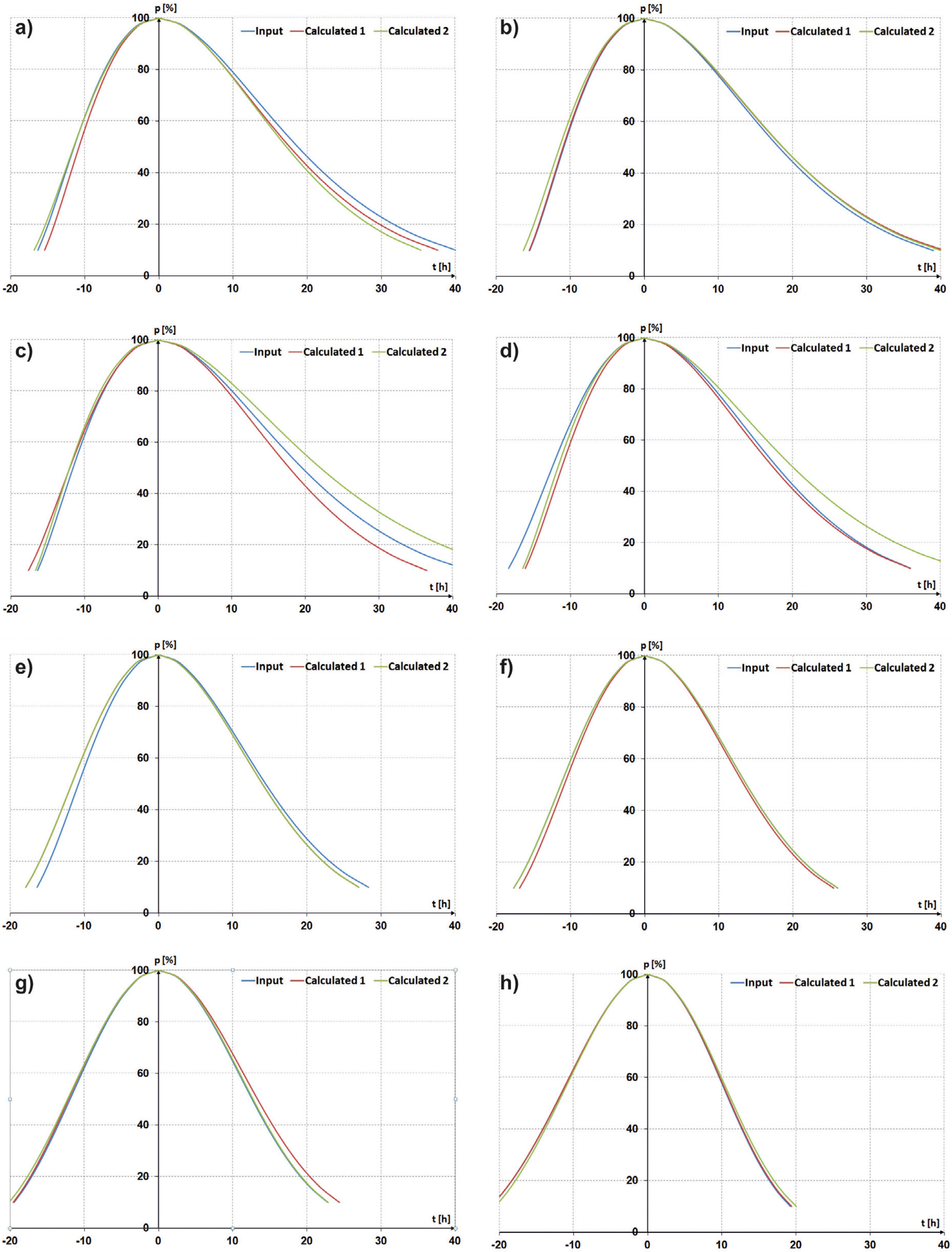

Fig. 5. Parametric hydrographs, where Input denotes the hydrograph obtained from the values *W*50, *W*75, and *s* taken from the nonparametric Archer hydrograph; Calculated 1 denotes the hydrograph obtained from the values computed by formulae (9), (10) and (11); Calculated 2 denotes the hydrograph obtained from the values computed by formulae (12) and (13) – the Rabka gauging station on the Raba in 1990 (a) and 2012 (b); the Stróża gauging station on the Raba in 1990 (c) and 2012 (d); the Krzczonów gauging station on the Krzczonówka in 1990 (e) and 2012 (f); the Stradomka gauging station on the Stradomka in 1990 (g) and 2012 (h)

efficient s [%]; W_p is the hydrograph width at p = 50%, p = 75% or skewness coefficient s determined from the nonparametric design hydrograph [h]; is the hydrograph width at p = 50%, p = 75% determined from formulae (9), (10) and (11) [h].

According to the evaluation criteria, the qualities of the computed hydrograph widths *W*50, *W*75, and skewness coefficient s for both periods may be classed as good and very good. To obtain a more reliable evaluation, further criteria were applied, based on comparison of the volumes and centres of gravity of the computed hydrographs with the hydrographs obtained from real data.

The volume of the hydrograph above the p-percent flow, for p = 50% and p = 75%, was determined using the following definition (see Fig. 7):

$$V_p = \sum_{i=1}^{N_p} V_{p,i} \qquad (15)$$

where: V_p is the volume of the hydrograph above the p-percent flow, p = 30%; N_p is the number of percent flows exceeding the p-percent flow: 16 for p = 30%; $V_{p,i}$ is the partial volume of the hydrograph between successive p-percent flows.

The centre of gravity time coordinate was determined for the part of the hydrograph above the p-percent flow, p = 30% (see Fig. 7):

$$r_p = \frac{\sum_i^{N_p} V_{p,i}\, l_i}{\sum_i^{N_p} V_{p,i}} \qquad (16)$$

where: r_p is the time coordinate of the centre of gravity of the hydrograph above the p-percent flow, p = 30% [h]; N_p is the number of percent flows exceeding the p-percent flow, i.e. 16 for p = 30%; $V_{p,i}$ is the partial volume of the hydrograph between successive p-percent flows [h]; l_i is the time coordinate of the centre of gravity r_i of the partial volume [h]; r_i is the centre of gravity of the partial volume.

A comparison of volumes and centres of gravity of the hydrographs based on values computed using formulae (9), (10) and (11) with the hydrographs based on the values of *W*50, *W*75, and s found from the nonparametric Archer hydrograph is shown in Figure 8.

A comparison of the volumes and centres of gravity of the hydrographs based on values computed using formulae (12) and (13) with the hydrographs based on the values of *W*50, *W*75, and s found from the nonparametric Archer hydrograph is shown in Figure 9.

Table 5. Quality measures for relative errors of hydrograph width *Wp* and skewness coefficient *s*

quality	*W*50	*W*75	*s*
very good	<10%	<20%	<10%
good	<10%,15%)	<20%,40%)	<10%,15%)
weak	<15%,20%)	<40%,60%)	<15%,20%)
very weak	≥20%	≥60%	≥20%

Table 6. Percentage contributions of quality measures for relative errors of hydrograph width *W*50, *W*75 and skewness coefficient *s* for the periods 1961-1990 (1990) and 1983-2012 (2012)

quality	*W*50		*W*75		*s*	
	1990	2012	1990	2012	1990	2012
very good	100%	100%	87.5%	100%	87.5%	77.8%
good	0%	0%	12.5%	0%	12.5%	22.2%
weak	0%	0%	0%	0%	0%	0%
very weak	0%	0%	0%	0%	0%	0%

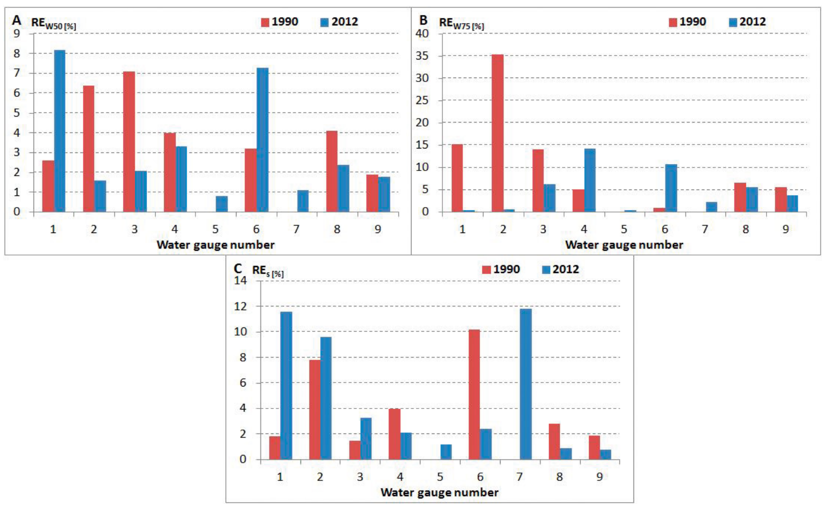

Fig. 6. Relative errors of hydrograph width *Wp*: A – for p = 50%, B – for p = 75%, C – for *s*, for the periods 1961-1990 (1990) and 1983-2012 (2012)

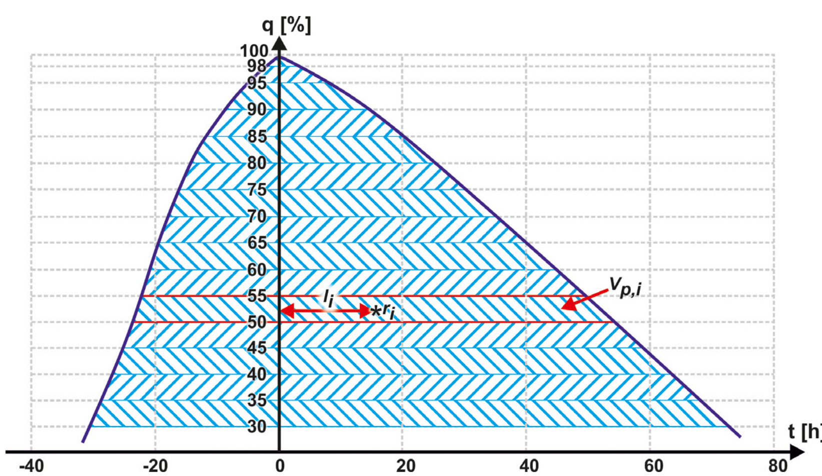

Fig. 7. Sketch for determining the partial volume of a hydrograph (trapezoid area) and the centre of gravity time coordinate used in equations 15 and 16

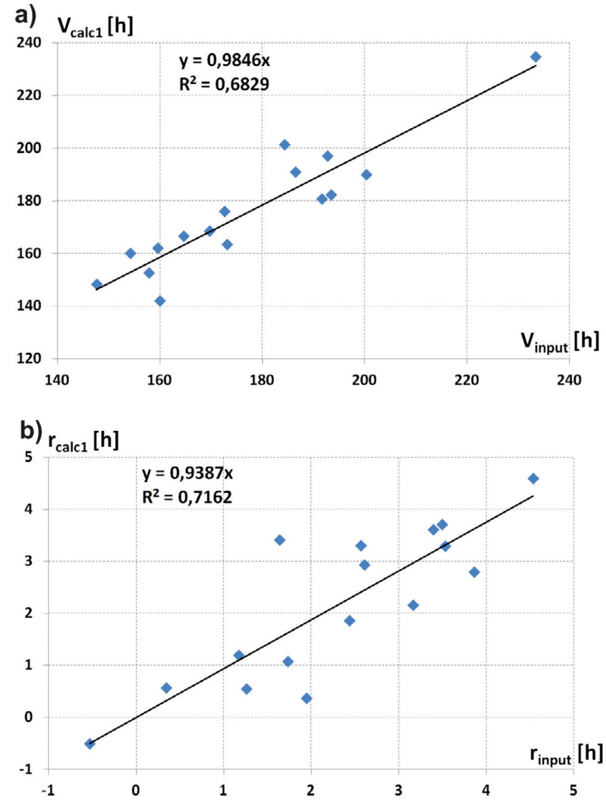

Fig. 8. Comparison of volumes (a) and centres of gravity (b) of parametric hydrographs computed using formulae (9), (10) and (11) with the volumes (a) and centres of gravity (b) of parametric hydrographs obtained using the values of *W50*, *W75*, and *s* found from the nonparametric Archer hydrograph

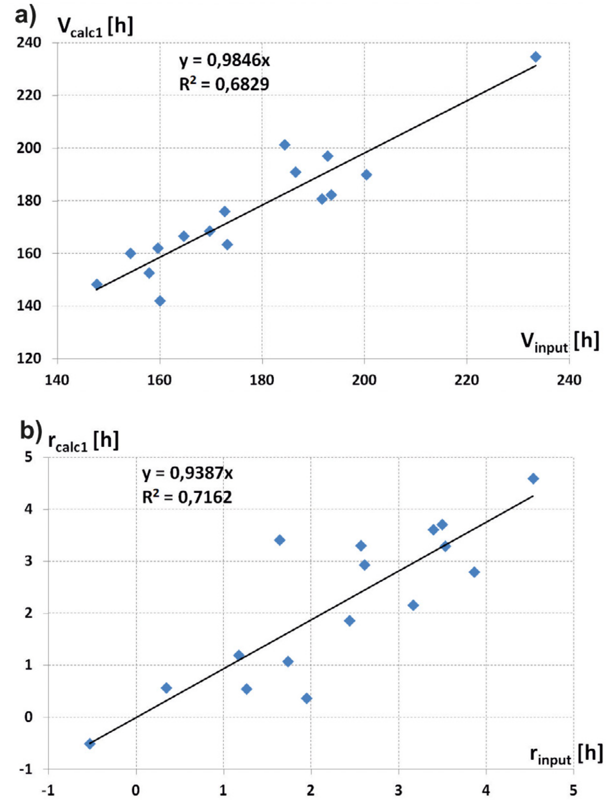

Fig. 9. Comparison of volumes (a) and centres of gravity (b) of parametric hydrographs computed using formulae (12) and (13) with the volumes (a) and centres of gravity (b) of parametric hydrographs obtained using the values of *W50*, *W75*, and *s* found from the nonparametric Archer hydrograph

5. SUMMARY AND CONCLUSIONS

The proposed empirical formulae enabling the determination of parametric flow hydrographs confirm the possibility of implementing methods developed in Western European countries for the purposes of hydrology in Poland. The two presented groups of formulas (9), (10), (11) and (12), (13) represent independent methods for obtaining parametric flow hydrographs. The first group relates to computation of the values of hydrograph width at p = 50%, p = 75% ($W50$, $W75$) and the skewness coefficient s, on the basis of which one may obtain a parametric hydrograph described by any function, e.g., the gamma density function, Baptista's gamma density function (Baptista 1990), the UPO-ERR gamma (O'Connor et al. 2014) or the Hayashi function (Hayashi et al. 1986). Thus, a parametric hydrograph can be determined in an optimum manner. In the case of the second solution the computed parameters are the wave shape n and the time to peak t_p for Baptista's gamma density function; this approach limits the freedom of choice of a function describing the parametric flow hydrograph.

The results for the catchment of the Raba River show that both solutions reflect the parametric flow hydrographs well. The agreement of the hydrographs in terms of volume and position of centre of gravity, as shown in Figures 8 and 9, is satisfactory for both methods. The coefficient of determination (R^2) for comparing the volumes of the hydrographs based on values of $W50$, $W75$, and s from the nonparametric Archer hydrograph with those of the parametric hydrographs using formulae (9), (10) and (11) is 0.68. When formulae (12) and (13) are used R^2 is 0.78. For comparing the centres of gravity of the hydrographs based on the values of $W50$, $W75$, and s from the nonparametric Archer hydrograph with those of the parametric hydrographs computed using formulae (9), (10) and (11), R^2 is 0.72, and when formulae (12) and (13) are used R^2 is 0.78. Comparing the position of centres of gravity checks that the volumes of the rising limb and the recession limb for the computed hydrograph agree with the hydrograph based on the values of $W50$, $W75$, and s found from the nonparametric Archer hydrograph. The computed relative error for the values of hydrograph width at p = 50%, p = 75% ($W50$, $W75$) and the skewness coefficient s, along with their quality measures, confirm the possibility of applying the formulae for their determination at any river cross-section; this is an advantage of the proposed solutions. The quality of fit for $W50$ is extremely high; for $W75$ and s it is slightly lower. It would therefore appear appropriate to verify whether the use of a value other than the hydrograph width at p = 75% might lead to a higher quality of fit of the hydrograph for that value.

The proposed solutions should be treated as verification of the possibility of implementing the methods applied in Western European countries for the purposes of hydrology in Poland. It is necessary to extend the field of study to other catchments and to verify how the quality of the results would be affected by using different physical catchment descriptors.

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Integrated assessment of change in contribution of excessive moisture to farming risks in the humid zone of Western Russia

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ABSTRACT. This paper is devoted to assessing the farming risks associated with excessive moisture effects in the Humid Zone of Western Russia over the past seven decades. The proposed spatiotemporal monitoring of the areas of this zone vulnerable to over-wetting allows us to evaluate the aggregate impact of climate variability and change on the degree of risk to farming over time. Furthermore, the detailed scale of the G.T. Selyaninov Hydrothermal Index (HTC) (with high values in July) is proposed to identify the recurrence and intensity of such risks as crop lodging under ongoing climate change (by comparing two 35-yr time intervals: 1945-1979 and 1980-2014). The functional analysis of HTC helps to show an increasing contribution of extreme precipitation totals to lodging intensity in comparison with cumulative air temperature contribution in recent decades, even in cases when air temperature sums have a tendency to increase. Moreover, the regression relationships between high precipitation totals and high HTC values are revealed more distinctly in the time interval of 1980-2014 due to a decrease in the residual variance. The comparative analysis of empirical distributions of total seasonal precipitation deviations from trends within time intervals 1946-1980 and 1981-2015 also confirmed the increasing recurrence of marginal positive anomalies in summer and autumn precipitation totals in the time interval of 1981-2015. In conclusion, the effects of excess moisture on the sustainability of regional crop production are assessed, and adaptation strategies are discussed.

KEYWORDS: Humid zone, climate change, excessive moisture effects, farming risks.

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1. INTRODUCTION

The Humid Zone (HZ) of Western Russia comprises the European territory of the Russian Federation between 52-63°N and 28-53°E. This zone is characterized by flat relief and predominantly podzolic soils with high moisture content. In recent years, a sharp increase in precipitation totals, especially in summer, has led to significant losses in the crop production in this zone due to crop over-wetting across large areas, including drained lands.

According to the climate change scenarios for European regions with cool temperate climate, further increase in annual precipitation totals accompanied by rising mean annual air temperature is predicted (Kjellstrom et al. 2011; IPCC 2014; Katssov et al. 2017). Thus, crop production is expected to be very vulnerable to the impending climatic changes in the HZ. This research has been conducted primarily to assess the observed changes in precipitation and also to evaluate impacts on the sustainability of regional cropping systems given the increasing recurrence and degree of farming risks caused by excessive moisture.

Here, the focus is put on the assessment of such risks during the warm period of the year. Some earlier efforts to assess climate change impacts on crop yield risk have been partially used in this research (Eitzinger et al. 2007; Nikolaev 2010, 2015a, b, 2016, 2017, 2018).

2. MATERIALS AND METHODS

The 70-yr monthly precipitation and mean monthly air temperature data (1945-2015) were obtained from the stations located within the territory under study. These data were transformed into agroclimatic variables for the intensive growth season, i.e. May, June, and July. The following aspects were considered in developing our methodology: selecting the agroclimatic indicators and time intervals; development of spatiotemporal monitoring of at-risk farming areas; comparison of the changing contribution of precipitation and thermal conditions to the intensity of farming risks, etc. The principal methods are functional and statistical analysis, including trend and residual analysis.

3. APPROACHES AND RESULTS

3.1. SPATIOTEMPORAL MONITORING OF FARMING RISKS

Among climatic indicators are those based on long-term agrometeorological observations of growth conditions during the vegetation season. Table 1 presents the agroclimatic indicators of emerging farming risks associated with excessive moisture effects during the warm months, as proposed by I.A. Gol'tsberg and A.D. Pasechnjuk (Sinitsina et al. 1973; Pasechnjuk 1990).

Based on these indicators, spatiotemporal monitoring of crop areas with different percentages of years with crop waterlogging and lodging effects in the changing climate conditions has been conducted, using a 5-yr step shift with-

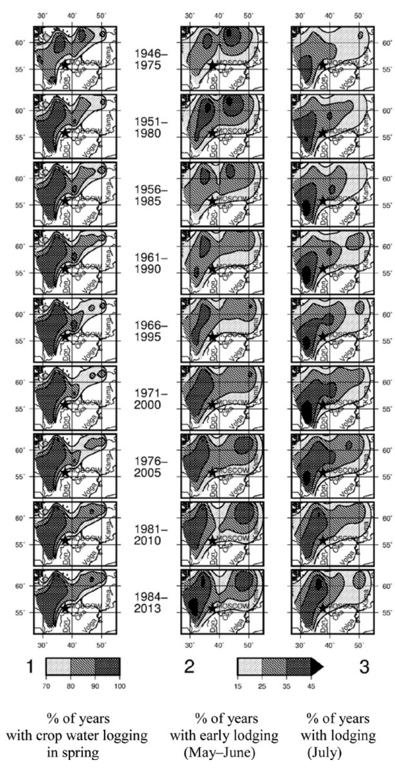

Fig. 1. Monitoring of crop areas vulnerable to excessive moisture effects during warm period (HZ of Western Russia)

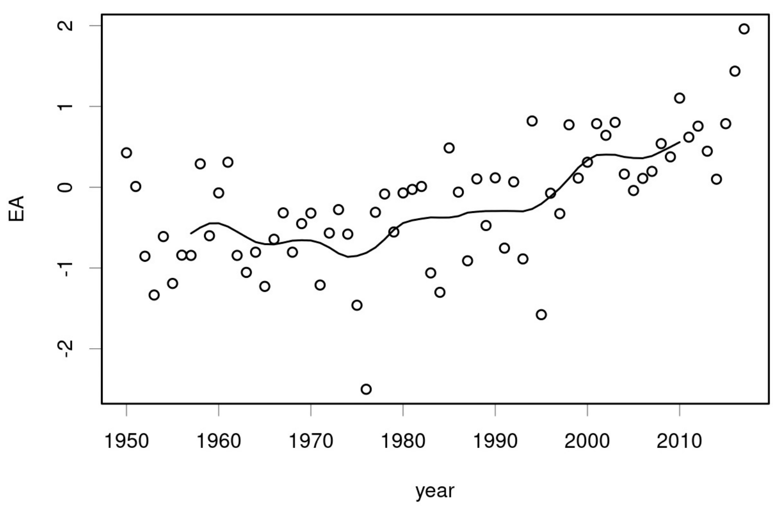

Fig. 2. Dynamics of the summertime EA indices (June-August) from 1950 to 2017 and 7-yr moving averages (the Gaussian filter is used)

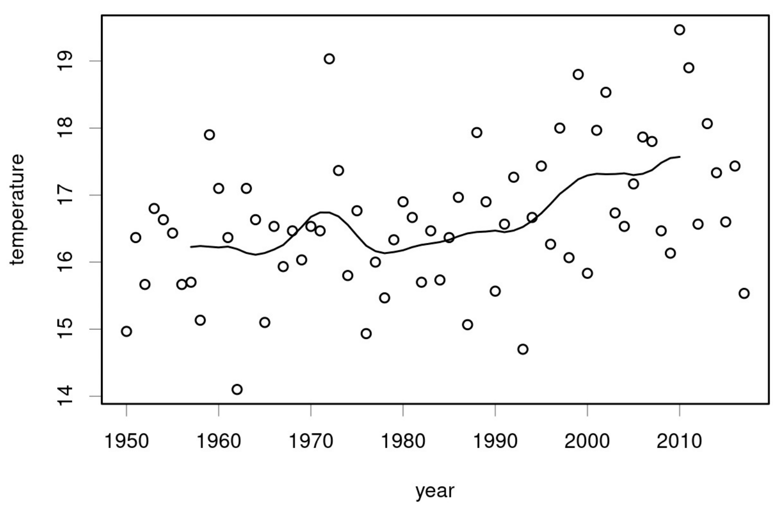

Fig. 3. Dynamics of summer air temperature (June-August) since 1950 to 2017 and 7-yr moving averages (the Gaussian filter is used) at Pskov: 57.8°N, 28.4°E

in the 30-yr observed period beginning in 1946 (Nikolaev 2017). Figure 1 illustrates the spatial dynamics of the vulnerable areas.

The optimal configuration of isoline-contoured areas with varied recurrence of farming risks employed GIS interpolation methods, such as kriging (Silkin 2008). This technique enables visualization of temporal changes in the boundaries of vulnerable areas relative to those for the baseline climate conditions (in the observed period 1961-1990). Obviously, the most extensive vulnerable areas are noticeable within the recent 30-yr period (predominantly the years after 1980) in comparison with the earlier 30-yr period. The occurrence of areas most vulnerable to the risk of early lodging in the northern regions of the HZ within the 30-yr periods 1946-1975 and 1951-1980 is explained by the prevalence of low air temperatures in May-June, along with precipitation amounts close to the long-term mean value. At the same time, there was some reduction in the size of areas vulnerable to the risk of lodging for the period 1984-2013. This observation is accounted for by the diminishing number of years with excessively wet conditions after 2005, and emergence of extremely dry conditions in July 2010 and July 2012 in the southwestern and central parts of the HZ.

3.2. COMPARATIVE ANALYSIS OF FARMING RISKS CAUSED BY EXCESSIVE MOISTURE EFFECTS IN THE CHANGING CLIMATE CONDITIONS

For comparative analysis of farming risks within the HZ, it is convenient to subdivide the period from 1945 to 2014 into two 35-yr intervals: 1945-1979 and 1980-2014. The rationale for this subdivision includes: (1) the increase in cyclonic activity at the middle-high latitudes in recent decades, and (2) upward trends in the mean annual air temperature, observed for Russian regions since the 1980s (Nesterov 2003, 2009; Franzke, Feldstein 2005; Drozdov, Smirnov 2011; Murav'ev, Kulikova 2011; Katssov, Semenov 2014; Kulikova et al. 2015; Polonskij, Kibal'chich 2015; Kiktev et al. 2018). Moreover, according to our recent study, there is strong agreement between the dynamics of 7-yr moving averages of the summer East Atlantic pattern (EA) indices and 7-yr moving averages of summer air temperatures in the time interval 1981-2017 (see Figures 2 and 3). It should be noted that the 68-yr dynamics of summer EA indices include an inflection point observed in approximately 1980.

This inflection point is very important as it is related to the northern expansion of crop areas of small cereals, maize hybrids, sunflower and fiber flax, as well as highly productive seed grasses.

Selyaninov Hydrothermal Index values for July (HTC_{VII}) are proposed for identifying the intensity and recurrence of farming risk from root and stem lodging in the changing climate conditions:

- $1.8 \leq HTC_{VII} \leq 2.5$ (perceptible root-stem lodging);
- $2.5 < HTC_{VII} \leq 3.5$ (severe root-stem lodging);
- $3.5 < HTC_{VII} \leq 4.5$ (very severe root-stem lodging);
- $HTC_{VII} > 4.5$ (extremely severe root- stem lodging)

The proposed scale reflects the increasing effects of both incessant and heavy rain on the lodging rate of example crops and their varieties due to the emerging conditions that lead to thinning of the soil surface and increasing mechanical load on stems, despite the application of short-statured cultivars in some regions (Gringof 1986). Simultaneously, the percentage of crop areas subjected to root-stem lodging increases with time.

Table 2 demonstrates an increase in the percentage of years with greater intensity of root-stem lodging during 1980-2014 compared to 1945-1979.

Table 1. Farming risks associated with excessive moisture effects during the warm period

Farming risk	Agroclimatic indicator of occurrence
Crop water logging in spring	$\sum P_{IX\text{-}III} \geq 230$ mm
Early root-stem lodging	$HTC_{V\text{-}VI} \geq 1.8$
Root-stem lodging in ordinary dates	$HTC_{VII} \geq 1.8$

Note: $\sum P_{IX\text{-}III}$ is precipitation totals for September-March; $HTC_{V\text{-}VI}$ is the G.T. Selyaninov's Hydrothermal Index for May-June; HTC_{VII} is the G.T. Selyaninov's Hydrothermal Index for July; *HTC* is a ratio of precipitation sums to air temperature sums with proportional coefficient equals 10 (Selyaninov 1958)

Table 2. Recurrence of root-stem lodging with different intensity [% of years] in the time intervals of 1945-1979 and 1980-2014 in the HZ of Western Russia

Station name with geographic coordinates	Root-stem lodging category							
	Perceptible $1.8 \leq HTC_{VII} \leq 2.5$		Severe $2.5 < HTC_{VII} \leq 3.5$		Very severe $3.5 < HTC_{VII} \leq 4.5$		Extremely severe $HTC_{VII} > 4.5$	
	1945-1979	1980-2014	1945-1979	1980-2014	1945-1979	1980-2014	1945-1979	1980-2014
Pskov 57.8°N; 28.4°E	29%	9%	**9%**	**11%**	0%	0%	0%	0%
Smolensk 54.5°N; 32.3°E	**20%**	**26%**	17%	9%	6%	6%	**0%**	**3%**
Trubchevsk 52.6°N; 33.8°E	**14%**	**23%**	20%	9%	**0%**	**3%**	0%	0%
Kostroma 57.7°N; 40.8°E	**17%**	**23%**	9%	6%	6%	3%	0%	0%
Petrozavodsk 61.8°N; 34.3°E	**17%**	**20%**	11%	9%	**0%**	**3%**	0%	0%
Vytegra 61.0°N; 36.4°E	**17%**	**29%**	11%	11%	**0%**	**3%**	0%	0%
Vologda 59.3°N; 39.9°E	17%	9%	**9%**	**20%**	0%	0%	0%	0%
Shenkursk 62.1°N; 42.9°E	**9%**	**17%**	9%	9%	0%	0%	0%	0%
Kotlas 61.2°N; 46.7°E	**14%**	**17%**	11%	6%	3%	3%	0%	0%
Syktyvkar 61.7°N; 50.8°E	**14%**	**23%**	**6%**	**14%**	3%	0%	0%	0%

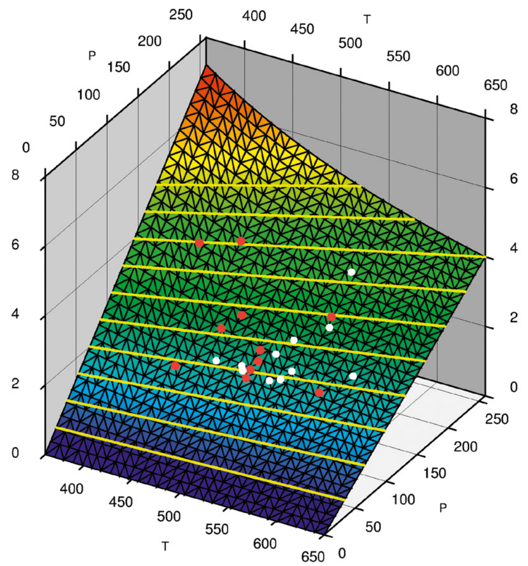

Fig. 4. Three-dimensional representation of the *HTC* values ≥1.8 for July; Kostroma: 57.7°N, 40.8°E (forest belt of the HZ); red dots – time interval of 1945-1979, white dots – time interval of 1980-2014

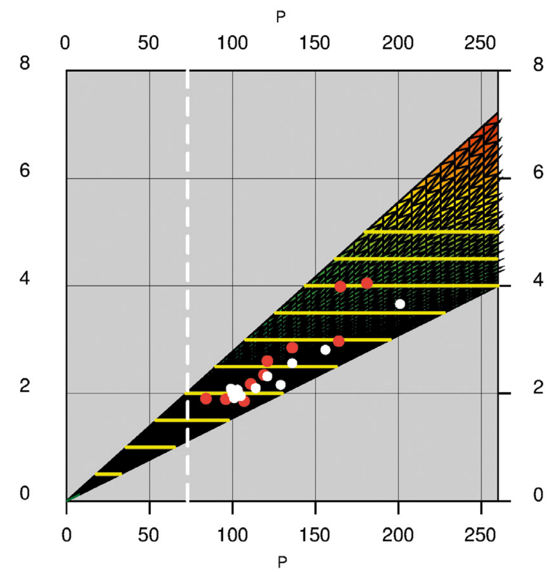

Fig. 5. Change in contribution of abundant precipitation in July to high HTC_{VII} values Kostroma: 57.7°N, 40.8°E (forest belt of the HZ); horizontal axis: precipitation sums for July [mm], vertical axis: the *HTC* Index values for July; dotted line: 70-yr mean of precipitation amounts for July equals of $\sum P_{VII}$ = 73 mm

This table also shows a number of cases where the percentage of years with perceptible and severe root-stem lodging in the northern regions during 1980-2014 is similar to that in the southern regions during 1945-1979. This fact has been analyzed in detail previously to establish the spatiotemporal analogue within the HZ (Nikolaev 2015a).

3.3. ASSESSMENT OF THE CHANGING CONTRIBUTIONS OF PRECIPITATION AND THERMAL CONDITIONS TO THE INTENSITY OF FARMING RISKS

Functional analysis (Kolmogorov, Fomin 1976; Nikolaev 2016) has been applied to assess the changing contributions of precipitation and thermal conditions to the intensity of farming risks. The *HTC* index is a function of two variables: the precipitation totals and the cumulative air temperatures (degree-days), i.e. a surface with two horizontal axes – the precipitation sums and air temperature sums and a vertical axis – the *HTC* index. For example, Figure 4 shows the 3-dimensional representation of the *HTC* index with the plotted *HTC* index values ≥1.8 for the two time intervals of 1945-1979 and 1980-2014 at Kostroma. For convenient visual assessment of how the dot clouds shift, the isolines are plotted with intervals of 0.5 in the *HTC* index.

The contribution of each factor to high *HTC* values can be assessed, as well as the variation in *HTC*, by means of this surface projection. The criterion of this assessment is based on the proximity of relationships shown in Figures 5-9. The conclusion may be made that the July precipitation totals make a governing contribution to the lodging intensity, compared to the July air temperature totals. Simultaneously, Figures 5-7 demonstrate the increasing contribution of the extreme precipitation totals in July to the lodging intensity during 1980-2014 in different parts of the HZ. This contribution accounts for the fact that the dots are located on a straight line, reflecting the decrease in the residual variance.

Figures 8 and 9 show the changing contribution of cumulative air temperatures to the high HTC_{VII} values at Smolensk and at Vytegra. A general drift of dot clouds towards the air temperature totals less than their 70-yr mean values is observed, which corresponds to the usual conditions when lodging occurs. Nevertheless, the dots related to 1980-2014 are plotted a bit to the right, i.e. high and very high HTC_{VII} values are observed at the higher air temperature totals. Figure 9 also shows that in the northern regions of the HZ extremely high HTC_{VII} values are observed even at air temperature totals noticeably higher than their 70-yr mean values during 1980-2014.

For example, at Kotlas (61.2°N, 46.7°E) the extremely high HTC_{VII} value of 4.14 occurred in 2000 when the air temperature totals exceeded the 70-yr mean value (515°C) by almost 100°C, and exceptionally high total precipitation in July exceeded the 70-yr mean value (72 mm) by 177 mm.

3.4. ASSESSMENT OF THE CHANGING CONTRIBUTION OF SEASONAL PRECIPITATION TOTALS TO RECURRENCE OF FARMING RISKS

It is known that crop farming in the HZ often is subjected to adverse effects due to the abundant precipitation over the year. Therefore, statistical methods are used for analyzing the empirical distributions of the deviations of seasonal precipitation totals around the trends (Kovalenko, Filippova 1982). Linear trend models (Anderson 1971) are applied to account for the high interannual and intra-seasonal variability in the precipitation totals. A comparison is made for the periods 1946-1980 and 1981-2015 (Nikolaev 2018). Figures 10-12 are histograms of deviations in seasonal precipitation totals from trends in both time intervals for several stations located in different parts of the HZ. For each histogram, both the equation of the linear trend and parameters of the empirical distribution of residuals, i.e. standard deviation (*s*), skewness (s) and kurtosis (k), are presented.

A significant increase in *s* for summer precipitation totals is observed for 1981-2015 (1.6 greater than *s* for 1946-1980) because of the marginal positive anomalies caused by the extremely high precipitation totals

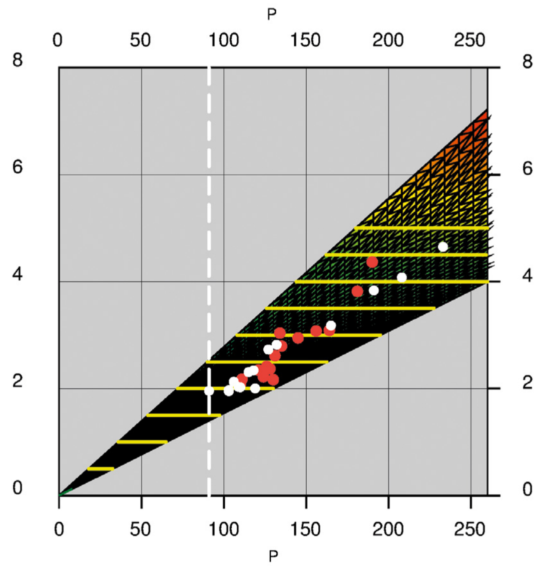

Fig. 6. Change in contribution of abundant precipitation in July to high HTC_{VII} values Smolensk: 54.5°N, 32.3°E (forest belt of the HZ); horizontal axis: precipitation sums for July [mm], vertical axis: the *HTC* Index values for July; dotted line: 70-yr mean of precipitation amounts for July equals of $\sum P_{VII}$ = 91 mm

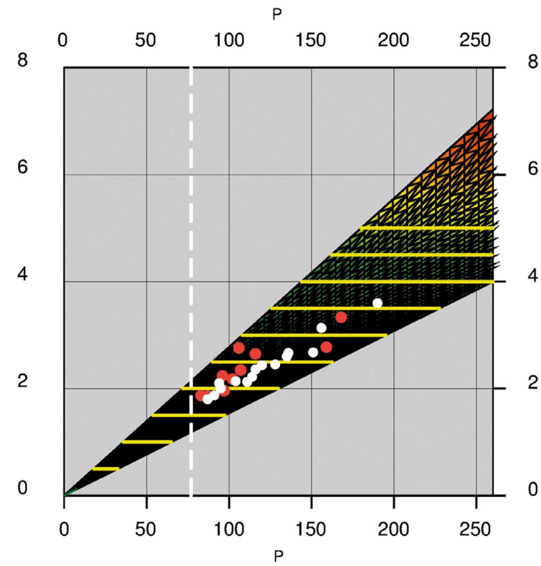

Fig. 7. Change in contribution of abundant precipitation in July to high HTC_{VII} values Vytegra: 61.0°N, 36.4°E (subboreal forest belt of the HZ); horizontal axis: precipitation sums for July [mm], vertical axis: the *HTC* Index values for July; dotted line: 70-yr mean of precipitation amounts for July equals of $\sum P_{VII}$ = 77 mm

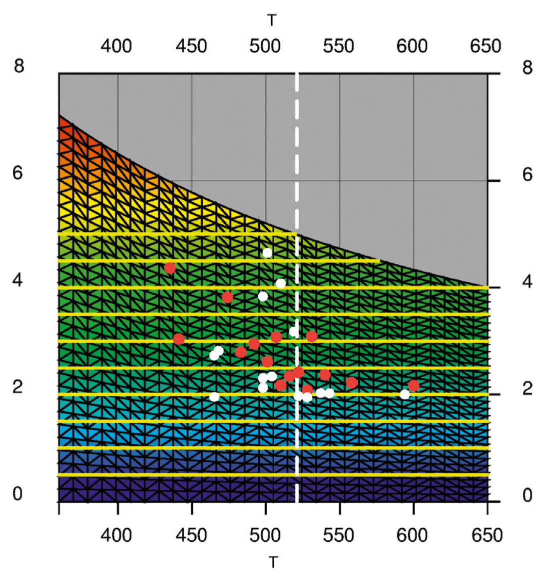

Fig. 8. Change in contribution of cumulative air temperatures for July to high HTC_{VII} values; Smolensk: 54.5°N, 32.3°E (forest belt of the HZ); horizontal axis: cumulative air temperatures for July [°C], vertical axis: the *HTC* Index values for July; dotted line: 70-yr mean of cumulative air temperatures for July equals of $\sum T_{VII}$ = 521°C

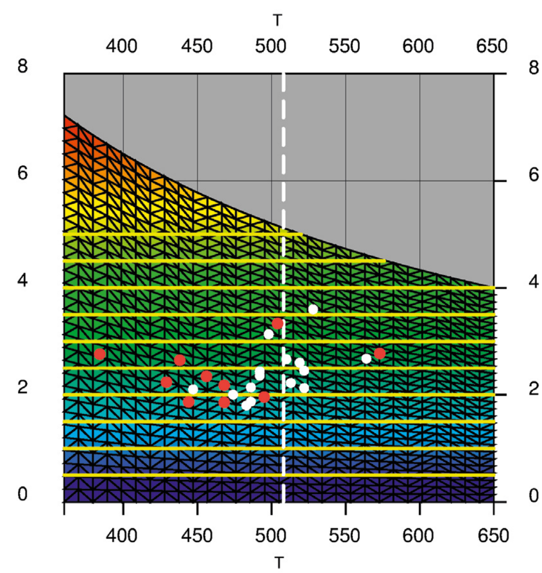

Fig. 9. Change in contribution of cumulative air temperatures for July to high HTC_{VII} values; Vytegra: 61.0°N, 36.4°E (sub-boreal forest belt of the HZ); horizontal axis: cumulative air temperatures for July [°C], vertical axis: the *HTC* Index values for July; dotted line: 70-yr mean of cumulative air temperatures for July equals of $\sum T_{VII}$ = 508°C

in summer at Pskov (western part of the HZ), see Figure 10. At the same time, the skewness of all distributions for the 2nd interval is positive and larger, excluding the spring season. The kurtosis is also larger, excluding the spring season.

For the same reason, the high *s* for summer precipitation totals is observed for 1981-2015 (1.3 greater than *s* for 1946-1980) at Vologda (eastern part of the HZ); see Figure 11. Meanwhile, the skewness changes sign between the winter and autumn seasons. Thus, the skewness is positive for the distribution of autumn precipitation in the second time interval (with increasing *s*), whereas the skewness is negative for the 1st time interval. The kurtosis differs insignificantly for all distributions, except for summer.

Although *s* values are greater for all seasons during 1981-2015 in comparison with those during 1945-1980 at Syktyvkar (the northeastern part of the HZ), the skewness is negative for summer precipitation totals in the 2nd time interval; see Figure 12. The kurtosis is greater in the 2nd time interval, except for winter.

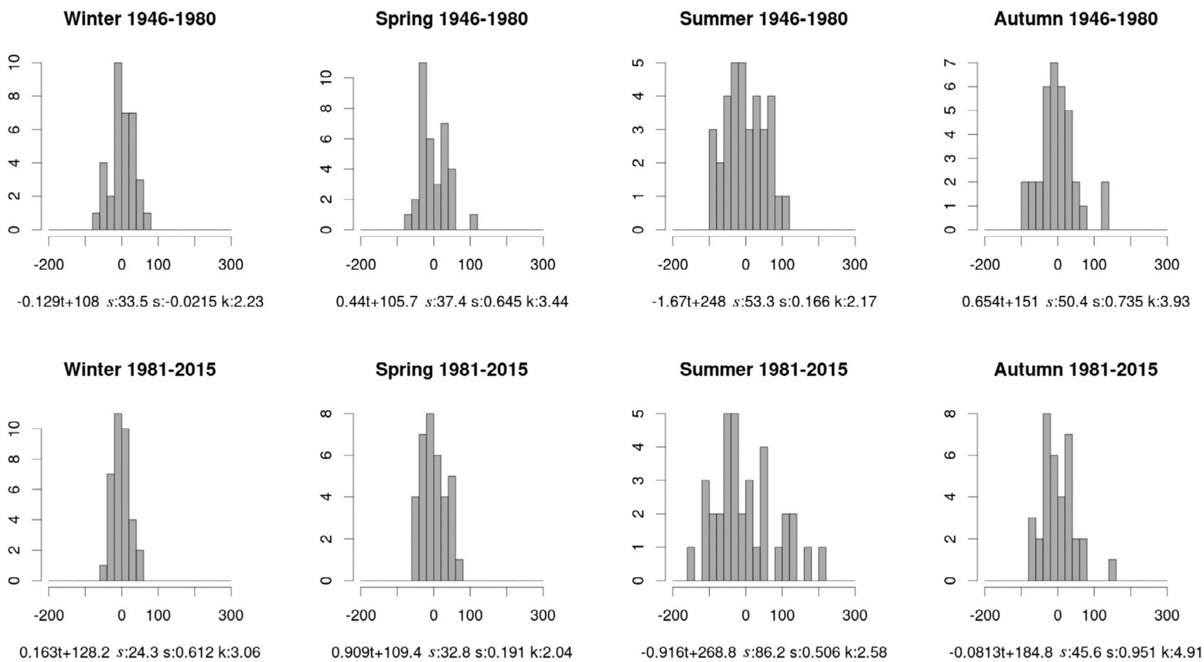

Fig. 10. Empirical distributions of seasonal precipitation totals in the time intervals of 1946-1980 and 1981-2015; Pskov: 57.8°N, 28.4°E (forest belt of the HZ)

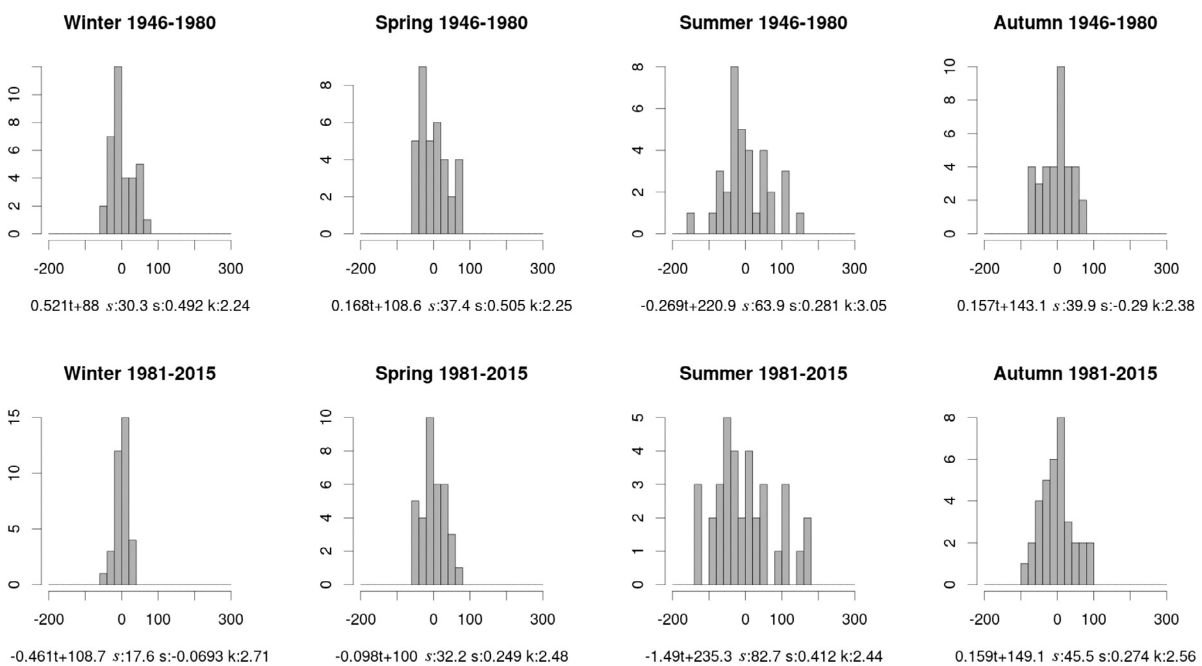

Fig. 11. Empirical distributions of seasonal precipitation totals in the time intervals of 1946-1980 and 1981-2015; Vologda: 59.3°N, 39.9°E (forest belt of the HZ)

3.5. ASSESSMENT OF EXCESSIVE MOISTURE EFFECTS ON THE SUSTAINABILITY OF CROP PRODUCTION

To assess excessive moisture effects on sustainability of crop production in the HZ of Western Russia, we analyzed the dynamics of yield losses with respect to technological trends in crop yields. Among small cereals, such crops as winter rye and winter wheat were revealed to be the most vulnerable. Then, yield losses of these crops were compared with several moisture indicators such as summer precipitation totals, $HTC_{V\text{-}VI}$, HTC_{VII}, $HTC_{VII\text{-}VIII}$ and summer EA indices. Thus, during 1945-1979 there were significant yield losses, corresponding to the excessively wet years 1950, 1958, and 1961. These yield losses were 10-15% greater than yield losses in extremely dry years such as 1972 and 1975. For example, in 1958 yield losses of winter rye at Shenkursk exceeded 29% (summer precipitation was 383 mm, $HTC_{V\text{-}VI}$ = 3.09, HTC_{VII} = 1.58, $HTC_{VII\text{-}VIII}$ = 1.96, summer EA index value = 0.29); in 1961 yield losses of winter rye at Vytegra exceeded 36% (summer precipitation was 462 mm, $HTC_{V\text{-}VI}$ = 1.40, HTC_{VII} = 3.33, $HTC_{VII\text{-}VIII}$ = 4.22, summer EA index value = 0.31).

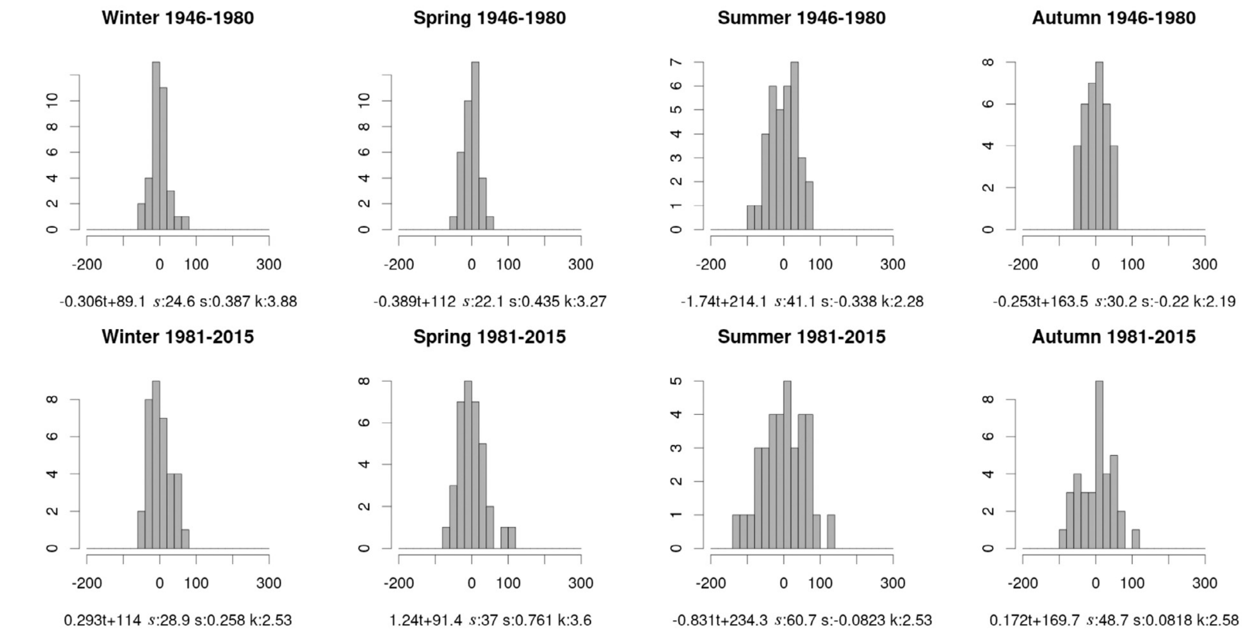

Fig. 12. Empirical distributions of seasonal precipitation totals in the time intervals of 1946-1980 and 1981-2015; Syktyvkar: 61.7°N, 50.8°E (sub-boreal forest belt of the HZ)

For 1980-2014 the absolute yield losses related to excessively wet years were noticeably greater than those during 1945-1979. This effect was a result of large upward trends in crop yields and also of a significant increase in precipitation amounts in the 1993-2008 period. Significant yield losses of indicated crops were recorded at Vologda in 1993 (35%), at Kotlas in 2000 (37%), at Kostroma in 2003 (22%) and at Petrozavodsk in 2008 (31%). The year 1998 was the wettest since 1945, and this agricultural year was considered most unfavorable for regional crop production. For example, yield losses of winter rye at Smolensk exceeded 54% (summer precipitation was 459 mm, $HTC_{V\text{-}VI}$ = 2.19, HTC_{VII} = *4.64*, $HTC_{VII\text{-}VIII}$ = 4.29, summer EA index = 0.77); yield losses of winter rye at Pskov reached up to 37% (summer precipitation was 457 mm, $HTC_{V\text{-}VI}$ = 3.32, HTC_{VII} = 3.42, $HTC_{VII\text{-}VIII}$ = 2.79, summer EA index = 0.77). It is noted that these losses are greater than yield losses observed in the extremely dry year 2010 (at Smolensk in 2010 yield losses of winter rye amounted to 24%, at Pskov in 2010 yield losses of winter rye amounted to 20%). According to available data, the year 2017 was an exceptionally wet year. For instance, yield losses of winter rye in this year at Vytegra exceeded 40% (summer precipitation was 406 mm, $HTC_{V\text{-}VI}$ = 2.40, HTC_{VII} = 4.61, $HTC_{VII\text{-}VIII}$ = 3.15, summer EA index = 1.96). It is characteristic that during past decades the most significant yield losses were observed in years with very high *HTC* values in July.

For soils of the HZ of Western Russia, the flushing type of water regime is typical, and the water table is near the surface in the northern and central parts of this zone. Field crops are mainly cultivated in the areas with sandy loam soils, medium-textured loam soils, and clay loam soils, due to limited distribution of sandy- and loamy-sand soils. Loam soils are less permeable than sandy soils, a fact reflected in greater yield loss at Smolensk (modal gleysolic podzol, medium-textured loam soil), than at Pskov (weak podzol, loamy sand soil) in 1998 as a result of over-wetting of the root layer.

The effects of water logging on winter crops in the early spring period typically are caused by the presence of lowlands and subnormal relief. However, these effects have been observed in recent decades more frequently, especially in the northeastern part of this zone, i.e., in the sub-region with loam soils with expressed gley horizon (e.g., at Vytegra, at Kotlas, and at Syktyvkar).

4. CONCLUSIONS

The results reported above give evidence of the increasingly negative effect of abundant precipitation on crop production in the HZ of Western Russia under ever-increasing climatic changes.

Spatiotemporal monitoring of the areas vulnerable to crop over-wetting reflects the aggregate impact of climate variability and change in the degree of risk for farming in the humid regions considered here. The change in the configuration of the vulnerable areas in recent decades is in good agreement with the increasing cyclonic activity over the North Atlantic. Meanwhile, a shift of the boundaries of the vulnerable area northward is observed, despite the concurrent rise in the surface air temperature. Specifically, the increase in the percentage of years characterized by emerging risks of different-intensity lodging in the HZ conforms with the specific features of such spatiotemporal modes as the North Atlantic Oscillation and the East Atlantic pattern.

The functional analysis enables us to distinctly differentiate the changing contribution of precipitation and thermal conditions to the intensity of risks associated with excessive moisture. Evidently, the graphs plotted show the ever-increasing contribution of the extreme precipitation totals to the lodging risk intensity compared to cumulative air temperature contribution, even in the cases when air temperature sums tend to increase (likely due to the increased contribution of both advective and convective types of precipitation).

The statistical analysis also confirmed the significant contribution of extreme summer precipitation to the emerging crop over-wetting risks. This fact demonstrates the increasing recurrence of the notable positive anomalies in the summer precipitation totals in different parts of the HZ during 1981-2015. At the same time, due to the more frequent occurrence of such anomalies in autumn, the harvest is made difficult or completely hindered, while unfavorable pre-wintering conditions for winter crops are also created.

It should be noted that the reliable regression relationships revealed during this research, in turn, make it possible to introduce more reliable extrapolation of the increasing lodging risks from predicted precipitation conditions in the nearest future. Furthermore, the observed trends in the changing precipitation and thermal conditions agree with the changes in air temperature and precipitation based on the transient GCM simulation for the long term. It provides the opportunity for better choices of the most probable scenarios for the climate in the future for further investigations.

On the other hand, the assessment presented serves as a basis for developing regional adaptation strategies. Specifically:

- improving tillage practice, namely: wide application of ridge and close-bed plowing in order to reduce the distance between the furrows to accelerate surplus water flow, as well as shallow plowing with rolling in the autumn to intensify surface runoff in the early spring;
- effective application of drainage systems: adjustment of pipe drainage capacity, use of surface drainage due to more frequent summer rains (in the waterlogged areas the creation of more frequent network of deep channels);
- smoothing and leveling of agricultural fields (in case of subnormal relief, displacement of crop areas from depressions to more high relief area);
- switching to more wet- and warm-weather crops and varieties in some sub-regions within the HZ (e.g., enlarging the crop areas under buckwheat as well as certain fodder and vegetable crops);
- enhancing disease control as well as pest- and weed control, especially for the species that are well adapted to wet conditions (e.g., the lodged crops are usually subjected to rust and mildew, and there are many aphids encountered in them)

In turn, these strategies may be expanded to the intra-regional levels, taking into consideration the local features of the crop production practice. Particularly, the results may be used in crop insurance; in decision-making for improving the water regime control in the agricultural fields; and in selective research related to prospective zoning of highly productive crops and their hybrids, etc.

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Data-driven discharge analysis: a case study for the Wernersbach catchment, Germany

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ABSTRACT. This study focuses on precipitation-discharge data-driven models, with regression analysis between the weighted maximum rainfall and maximum discharge of flood events. It is also the first of its kind investigation for the Wernersbach catchment, which incorporates data-driven models in order to evaluate the suitability of the model in simulating the discharge from the catchment and provide good insights for future studies. The input parameters are hydrological and climate data collected from 2001 to 2009, including precipitation, rainfall-runoff and soil moisture. The statistical regression and artificial neural network models used are based on a data-driven multiple linear regression technique, and the same input parameters are applied for validation and calibration. The artificial neural network model has one hidden layer with a sigmoidal activation function and uses a linear activation function in the output layer. The artificial neural network is observed to model 0.7% and 0.5% of values, with and without extreme values respectively. With less than 1% error, the artificial neural network is observed to predict extreme events better compared to the conventional statistical regression model and is also better suited to the tasks of rainfall-runoff and flood forecasting. It is presumed that in the future this study's conclusions would form the basis for more complex and detailed studies for the same catchment area.

KEYWORDS: Artificial Neural Networks, data-driven modelling, event-based coefficient of rainfall-runoff, precipitation, multi-correlation analysis, soil moisture content.

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1. INTRODUCTION

The transformation of rain into a runoff is a complex process that is difficult to fully understand (Hsu et al. 1995; Humphrey et al. 2016). The challenges faced are mainly linked to the non-stationary features of the phenomenon (e.g. trends, seasonality, and jumps) and a highly non-linear relationship between discharge and its driving variables (Cannas et al. 2006; Nourani et al. 2011). Hence, a reliable model for the simulation and prediction of the rainfall-runoff process is in demand, providing important information for integrated water resource management and planning.

With recent developments in computational intelligence, there has been a rapid expansion in the capabilities of empirical modelling, and in particular, in data-driven modelling (DDM). DDM is a fundamental analysis technique that uses the data characteristics of a system and requires less input as parameters compared to other models (Solomatine et al. 2008). As an empirical model, it applies mathematical equations in the analysis of concurrent input and output time series, for example, linear and multi-linear regressions (Clarke 1994).

The most popular computational techniques include artificial neural network (ANN) models, fuzzy rule-based systems (FRBSs), genetic algorithms (GAs), and approaches to model integration. ANN have been successfully applied in modelling rainfall-runoff processes e.g. Hsu et al. (1995), Minns and Hall (1996), Dawson and Wilby (1998), Dibike et al. (1999), Abrahart and See (2000), Abrahart et al. (2008). More specifically, Solomatine and Avila Torres (1996) replicated the behaviour of river basin hydrodynamic/hydrological models and proposed the optimal control of a reservoir, while Bhattacharya and Solomatine (2003) and Sudheer and Jain (2003) modelled stage-discharge relationships.

FRBSs have been successfully applied for drought assessment (Pesti et al. 1996), the prediction of precipitation events (Abebe et al. 2000b), the analysis of groundwater model uncertainty (Abebe et al. 2000a), the control of water levels in polder areas (Lobbrecht, Solomatine 1999) and the modelling rainfall-discharge dynamics (Vernieuwe et al. 2005). Moreover, GAs have been used to optimise DDM techniques, such as neural networks (Yao, Liu 1997). Khu et al. (2001) applied genetic programming to real-time runoff forecasting for a catchment in France, while Giustolisi and Savic (2006) used evolutionary regression for groundwater and river temperature modelling.

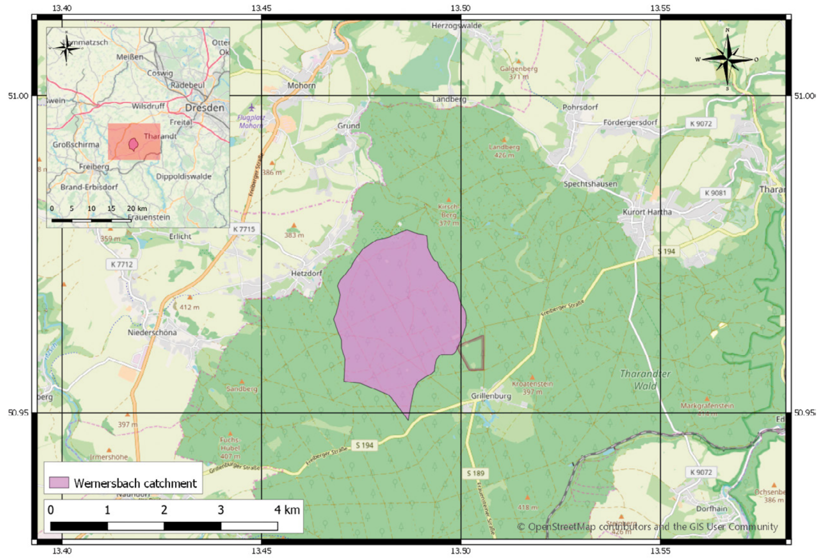


Fig. 1. Wernersbach catchment

The objective of our study is to perform a first of its kind investigation for the Wernersbach catchment, based on an approach incorporating two data-driven models, namely a statistical regression model and an artificial neural network model, in order to validate and add to better understanding on the suitability of the models for the catchment's discharge simulations. It also aims to provide good insights for future studies that would incooperate it's conclusion and develop on its limitations for future research studies.

2. STUDY AREA AND METHODOLOGY

The catchment area of the Wernersbach is located approximately 25 km southwest of Dresden, in the north-western region of the landscape conservation area of Tharandt Forest and the eastern part of the Ore Mountains (latitude 50°58'N, longitude 13°28'E). The area covers 4.6 km^2 and with an altitude above sea level within the range of 323-424 m.

The location of the catchment is depicted at the top left-hand side of in Figure 1, with the catchment location marked in red on the political boundary of Germany. In addition to this, Figure 1 presents the boundary of the Wernersbach catchment in purple and the river and surrounding areas in dark green.

The local topography and the dominance of forestry as the land usage type are observed to majorly contribute to the deviations from the average climatic conditions. The area mainly compromises low slopes of less than 3° (Bernhofer 2002). These small-scale relief forms have a great impact, as concave relief forms tend to lead to lower temperatures (cold-air formation), and convex relief forms generally exhibit higher temperatures in the winter. These differences in relief also influence incident radiation, wind and precipitation (Bernhofer 2002).

The climate is essentially characterized by maritime influences whereby the greatest amount of precipitation is observed during the summer months.

The mean annual temperature is 7.5°C, and the mean annual precipitation is approximately 847 mm (Goldberg, Bernhofer 2007). Groundwater occurs only in rhyolite rocks. Therefore, large fluctuations in groundwater levels can occur within a short time period (Gerold et al. 1998).

In the upper surface of the paleorhyolite (porphyry), weathering products exhibit strong cohesive properties. During the early cretaceous, small low-binder sandstones with embedded clay horizons were present in the area. These sandstones are effective in water management. At the layer boundaries of the sandstone and the porphyry layer sources, water discharges are also recorded. Moreover, further marine sandstone deposits have been preserved from the transitional time (i.e. the early cretaceous to the late cretaceous), with weathering products that are prone to frost formation.

The Wernersbach area is used exclusively for forestry purposes. Spruce is widely predominant and is used to strike other conifers and deciduous trees. In order to improve growth conditions for the forest stands at locations affected by water pollution, a dense net-

Table 1. Water balance components of the catchment Wernersbach (Goldberg, Bernhofer 2007)

Water Balance Components	Measure	Unit(s)
Precipitation	847	mm
Runoff	240	mm
Evapotranspiration	607	mm
Minimum runoff (mean)	2.5	litre/sec
Mean runoff	35	litre/sec
Maximum runoff (mean)	1,228	litre/sec
Maximum runoff (estimated)	80,00-10,000 (13.08.2002)	litre/sec

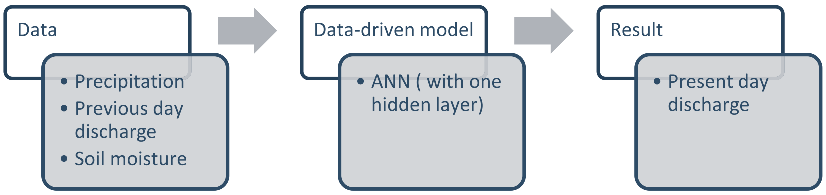


Fig. 2. Modelling process

work of artificial drainage trenches has been constructed (Bernhofer 2002).

The natural conditions of the Wernersbach catchment make it a suitable study area for the quantification and measurement of the water balance in space and time. The water balance components of the catchment are presented in Table 1.

This study uses climate and hydrological data from the Wernersbach catchment collected from 2001 to 2009. All data was initially stored on-site in data loggers and has a temporal resolution of one day. Field observation measurements used for the runoff models include the depth to groundwater table, precipitation, soil moisture at 30 and 60 cm and discharge.

2.1. ARTIFICIAL NEURAL NETWORK

ANN technology is a computational approach inspired by studies of the brain and nervous systems (Luk et al. 2001). The ANN technique has a number of interconnected processing elements that generally operate in parallel with regular configurations. These neural networks are capable of modelling both linear and non-linear systems (Riad et al. 2004).

There are two types of artificial neural networks: (i) the feed-forward neural network; (ii) recurrent/feedback networks. The multi-layer field network (MLF) is a typical feed-forward network where adjusted weight coefficients are calculated and outputs are highly accurate (Svozil et al. 1997). A very simple model based on historical data, namely, drawing a line to best separate between critical and non-critical conditions, is used for the MLF. The possible applications of this model include flash flood susceptibility analysis, evaluating the multi-correlation function between rainfall and runoff, soil moisture and the precipitation of a hydrological catchment area.

An MLF neural network consists of neurons that are ordered into layers. The first layer is denoted as the input layer, the last layer is the output layer, and the layers in between are hidden layers (Svozil et al. 1997). The model used in this study, presented in Figure 2, has one hidden layer with a sigmoidal activation function, and a linear activation function in the output layer. The network is prepared using a simple error backpropagation algorithm.

2.2. REGRESSION ANALYSIS

The regression analysis in its simplest form uses two variables, one as the dependent variable and the other as the independent variable, thus making it possible to study the cause and effect of the relationship. A linear regression model that involves more than one independent variable is known as a multiple linear regression (MLR) model. Multiple regression analysis is used to establish the statistical relationship between one dependent variable and one or more independent variables X_1, X_2, …, X_p and is of the form (1) (Jaya Rami Reddy 2013) the multiple regression equation. The term linear is used because equation (1) is a linear function of the unknown parameters b_0, b_1, …, b_p:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \ldots + b_p X_p \qquad (1)$$

In non-linear regression analysis, the dependent variables are modelled as a non-linear function of the model parameters and one or more independent variables (Bilgili 2010). The multiple non-linear regression model (MNLR) is a simple and efficient method in producing more accurate maximum daily discharge predictions compared to the ANN, the adaptive neuro-fuzzy interference system and the MLR (Rezaeianzadeh et al. 2014). The multiple non-linear regression equation generally is of the form (Jaya Rami Reddy 2013):

$$Y = b_0 X_1^{b1} X_2^{b2} \ldots X_p^{bp} \qquad (2)$$

where b_0, b_1, …, b_p are the parameters of the non-linear relationship. Multiple non-linear regression problems can be linearized using simple logarithmic transformation by taking the logarithms of both sides of equation (2) (Jaya Rami Reddy 2013):

$$\ln Y = \ln b_0 + b_1 \ln X_1 + b_2 \ln X_2 + \ldots + b_p \ln X_p \quad (3)$$

Moreover, the regression of $\ln Y$ on $\ln X_1$, $\ln X_2$, …, $\ln X_p$ is utilized for estimating b_0, b_1, …, b_p.

2.3. MODEL VERIFICATION

A statistical evaluation method can provide an indication of the best model, while the graphical and hydrological interpretation of the presented datasets and models can evaluate this simplistic indication. Based on their soundness and robustness, traditional log-log rating curves have been observed to be superior, regardless of their poor goodness-of-fit statistics (Abrahart et al. 2011).

2.4. AREAL PRECIPITATION

The Thiessen polygon method introduced by Thiessen (1911), is used here to determine the average amount of precipitation over the study area. It is a graphical technique that calculates areas relating to specifically placed rain gauges, deriving an areal value plus a reference, resulting in polygons within polygons (see Fig. 3).

3. GENERAL STUDY APPROACH

We assume an ideal prognosis using the observed precipitation and soil moisture data. This ideal prognosis of the meteorological input allows us to neglect prognosis uncertainties, which are mostly connected to modelled precipitation from dynamic weather forecast models. Therefore, the resulting model performances are mainly defined by the approaches themselves, rather than by accuracy of the data.

The basic architecture of the approach used in this study is presented in Figure 2. The three white boxes demonstrate the three basic steps, i.e. the data, the data-driven model and the result. The three grey boxes show the sub-routines. The first step consists of inputs that can influence the output, i.e. precipitation, previous day discharge, and soil moisture. The second step consists of the models used to analyze the inputs. The last or output step consists of the predicted values or results, i.e. present day discharge.

The validation strategy was used to create statistically robust results from 100 randomly chosen subsets, in order to quantify the impact of extremes in the prediction. Performance indices were used to compare the performance of both models, namely the coefficient of determination (4), the root mean square error (*RMSE*) (5) and the mean absolute percentage error (*MAPE*) (6).

$$R^2 = 1 - \frac{\Sigma_{i=1}^{n}(y_i - \hat{y}_i)^2}{\Sigma_{i=1}^{n}(y_i - \bar{y}_i)^2} \quad (4)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (5)$$

$$MAPE = \frac{100\%}{n}\sum_{i=1}^{n}\frac{[y_i - \hat{y}_i]}{y_i} \quad (6)$$

In the above equations, y_i represents the observed water discharge, represents the forecasted water discharage, represents the average observed water discharge and average predicted water discharge respectively, and *n* represents the number of observations in both calibration and validation stages.

The *R*-squared (R^2) value was used to measure how close the data is to the fitted regression line. It provides information on the strength of the linear relationships between the observed and predicted values. Moreover, the *RMSE* (5) represents the prediction of the errors in the model.

All analysis was performed using the R programming package. The Neuralnet R package was used for the ANN model. For the MLR model, an in-house script was written. The ANN model exhibited higher computing times due to the training of the neural network. One catchment at a time was used for both models due to the minimal amount of computer resources required for the MLR (statistical) and the ANN (data-driven). The model ensembles were then used to identify the best estimate for a flood event.

4. RESULTS AND DISCUSSION

The areal significance to the point rainfall values assigned by the Thiessen polygon method for five rain gauges are depicted in Figure 3. The respective sizes of the areas are reported in Table 2.

A relationship was derived between precipitation, soil moisture and discharge, considering days when precipitation was greater than 0.1 mm, and using daily soil moisture data and discharge values for previous days. During 2001-2009, 1,804 days were observed to have a precipitation value of more than 0.1 mm per day. In order to reduce random errors from using linear regression only once, the 1,804 events with precipitation values, rainfall-runoff, and soil moisture were randomly divided into two halves 100 times.

According to the results of the calibration and validation data sets, the median R^2 value for both data sets was observed as 0.887. This indicates a strong correlation between the considered variables. In addition, both data sets exhibit the same distribution shape (Figs. 4 and 5) for the determined R^2 values.

The logarithmic linear dependence can be expressed as follows:

$$\ln Q_{(0)} = 0.228 \ln Q_{(-1)} + 0.002\, Sw_{(-1)} + 0.9 \ln P_{(0)} - 0.215 \quad (7)$$

where *Q* represents discharge, *Sw* represents soil moisture, *P* represents precipitation, the indices 0 and –1 denote the current and previous day respectively.

The resultant model is characterized by the values of the selected performance indices presented in Table 3.

In Figure 6, Q_{mod} represents the modelled specific discharge, while Q_{obs} represents the observed specific discharge. Both values are converted to mm, in order to have the same units as precipitation and soil moisture. The conversion to discharge involves multiplying the specific discharge by the size of the Wernersbach catchment. The black line in Figure 6 represents the trend line without considering the extreme values, while the green line represents the trend line when extreme values are considered.

The trend lines demonstrate a consistency in the observed maximum values, particularly for the validation data set. Both data sets suggest that the model tends to slightly overestimate high flood events by 1.01% and 14% for the validation and the calibration data sets, respectively.

The range of predicted errors between the simulated value and the measured values for the statistical regression model is shown in Figure 8.

It should be noted that 1,798 rain events from the total 1,804 lie within the range of 0-13 mm, with the maximum (1,593 events) within in the range of 0-1 mm.

A good correlation between the simulated and measured specific discharge is observed for the range of 0-13 mm. In contrast, greater uncertainty is associated with discharge above 13 mm, due to the small number of precipitation events within 13-61 mm (only 6 events).

High uncertainty indicates a high demand for data and a small and responsive characterization of the catchment area. Under such conditions, it is difficult to predict any extremes.

The discharge value in the Wernersbach catchment depends primarily on precipitation. A close relationship between all three parameters is exhibited. A significant input from the soil moisture parameter can be observed during events with high discharge values. Using the median absolute deviation (MAD) method (Leys et al. 2013), 198 precipitation events were determined as "outliers" or bankful discharge. These events suggest a rise in discharge and flood, or high flood, events. Here, we denote them as extreme events.

Following its successful launch, the ANN model was validated. The MLR and ANN models' results are assessed with a statistical representation of the histograms and Q-Q plots. The data in both models runs are with and without extremes (the 198 events described earlier were excluded). Based on this, different scenarios are analyzed.

A perfect bell-shaped curve representing a normal distribution is observed where the allocated dataset does not include extreme values. The non-linear characteristic of the rainfall-runoff process is normalized using a logarithmic transformation. This transformation is applied in order to provide an improved fit of the R^2 values to the normal distribution (Fig. 9).

The *MAPE* value is observed as 153% for the MLR model and 140% for the ANN model. The *MAPE* errors demonstrate that the ANN model has a smaller variance in prediction errors than the MLR model compared to the original dataset scale.

We find that both models overestimate the simulated values. The dataset validation with extreme values for the MLR model is equal to 14%, while the ANN model demonstrates a lower error value of 0.7% for the dataset validation with extreme values and 0.5% without extremes values.

The above result implies that the ANN model better generalizes the variability of high

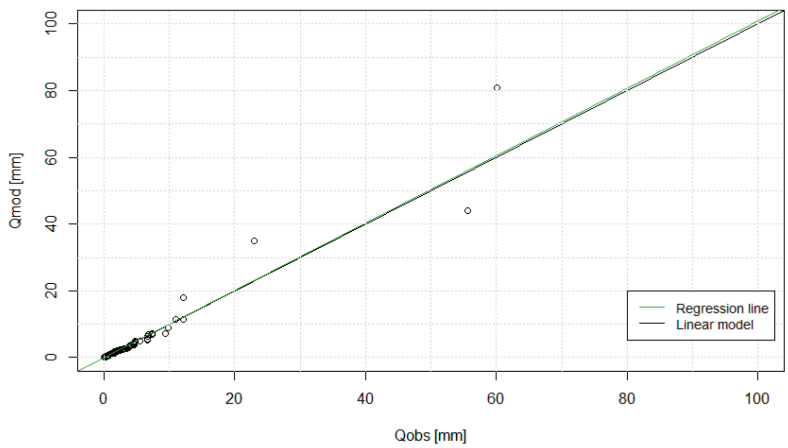


Fig. 7. Dependencies between the simulated and the measured values for the validation data set of the statistical regression model

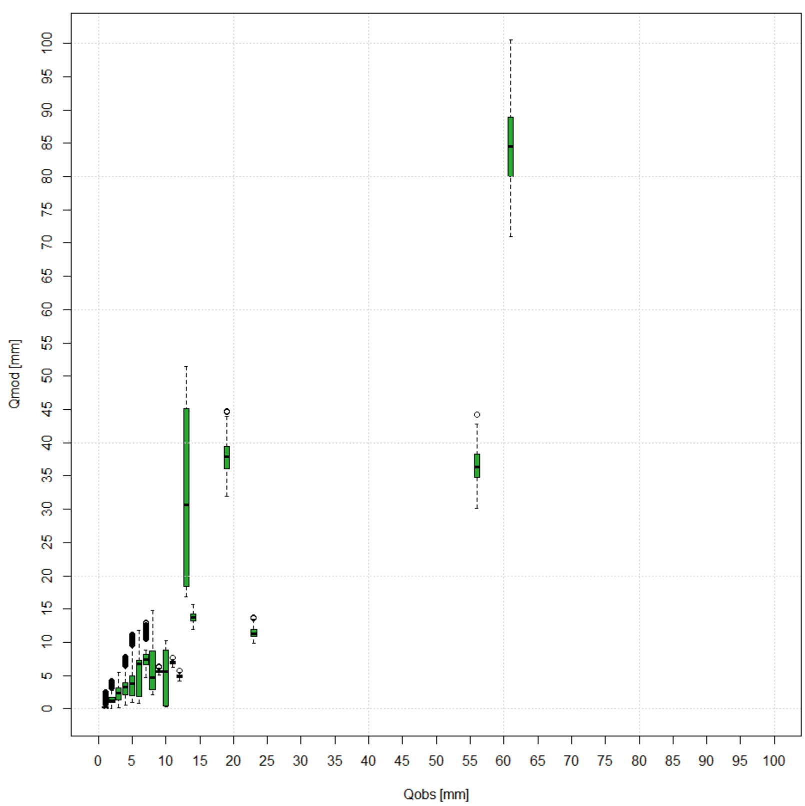


Fig. 8. Box plot showing the range of errors between the simulated and measured values for the statistical regression model

floods in the observation period compared to the MLR regression model. The results from the former can be considered more satisfactory over the whole period, with a large annual variability of extreme events. The estimates are sufficient to provide on-time warnings with minimal errors.

The snowmelt factor was not considered as influential in this study. However, including climate change as a driving factor and considering studies for an earlier initiation of the snowmelt season (Schneider, Schönbein 2005; Blöschl et al. 2017), increases the duration of the snowmelt season. Thus, it is important to include snow/ice –melt and temperature in the models in order to provide near real-time forecasts. This will be duly addressed in our future and on-going studies.

Soil moisture is often found to have a triggering influence on floods and is included in the models, depending on the availability of the measured input. In the typical data-poor conditions that characterize flash flood forecasting and warnings, surrogate indexes that implicitly consider the soil moisture initial state, are often extremely useful.

5. CONCLUSION

In this study, we investigate an approach incorporating data-driven modelling for the Wernersbach catchment with three observed parameters: (i) soil moisture, (ii) precipitation of the current day and (iii) precipitation from the previous day. An alternative model is run to compare and validate the results. Both models are on loop fast enough to include several statistical analysis methods, with an efficiency in forecasting results for time stringent cases. Based on the catchment characteristics, the model based on regression analysis is determined as a more effective statistical method for the estimation of flood discharge compared to other methods.

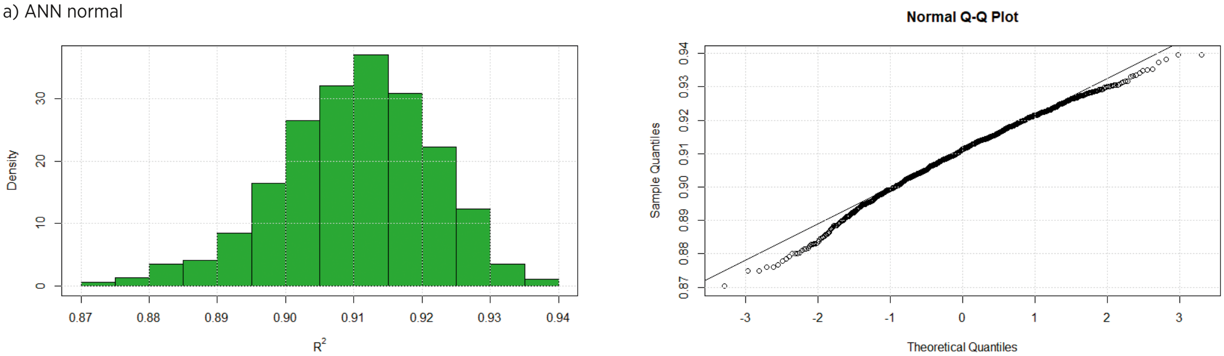
A more detailed alternative approach would involve the use of hydraulic formulae (e.g. Manning equation) or one- or two-dimensional hydraulic models (e.g. the Saint-Venant equations) to convert historical flood levels into historical discharges (Benito et al. 2004). Moreover, flash flood guidance, which tags the rainfall accumulation needed to produce a flood of a given magnitude according to current soil moisture conditions, has proven useful for ungauged basins (Borga et al. 2011).

For the Wernersbach catchment area, our results show that data-driven methods are a feasible alternative to the flash flood guidance approach. the ANN model is generally preferable, even for extreme events, compared to the MLR approach.

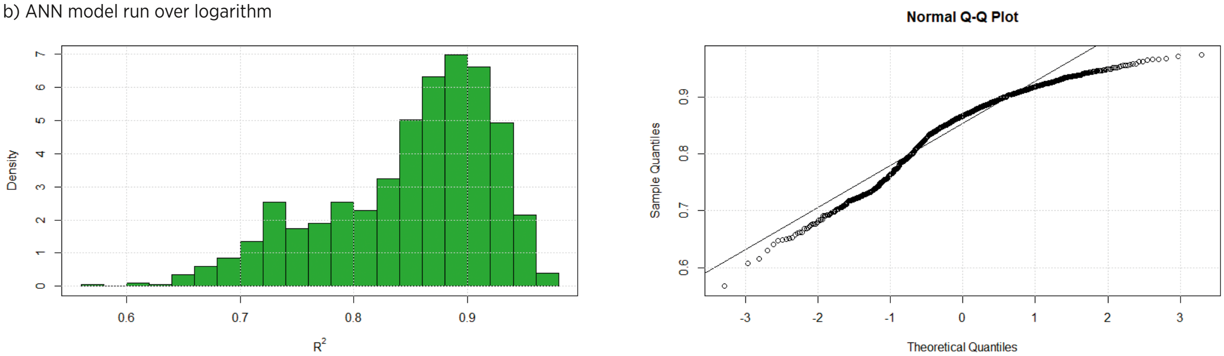
However, the considered temporal scale (2001-2009) do not include significant amount of past major hydrological extreme events and exclusion of uncertainties by climate change limits our study in various aspects. Despite these limitations, we are confident ANN model is better suited to the tasks of rainfall-runoff and flood forecasting over traditional MLR approach.

Nevertheless, as per our current knowledge, this study is the only one of its kind done over the Wernersbach catchment and is presumed to build foundation for further application of ANN models in research focusing on the influence of spatial and temporal rainfall patterns on the estimation of rainfall thresholds, as well as the prediction of soil moisture.

a) ANN normal



b) ANN model run over logarithm



c) MLR normal

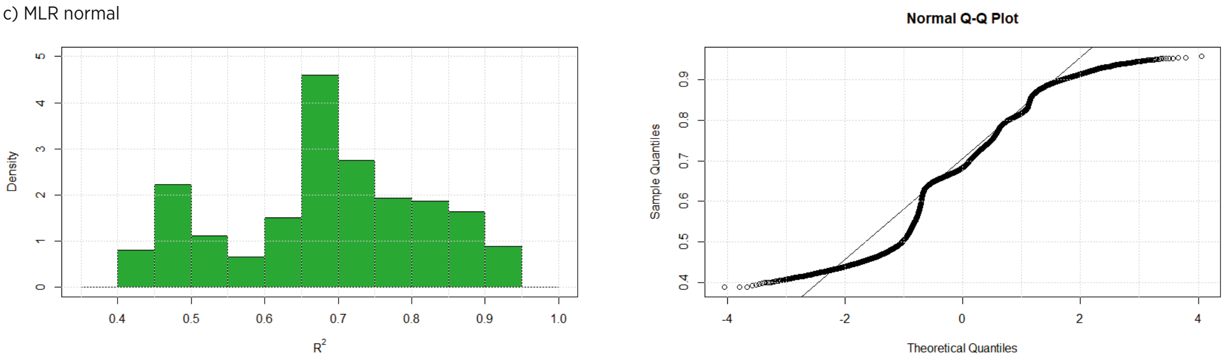
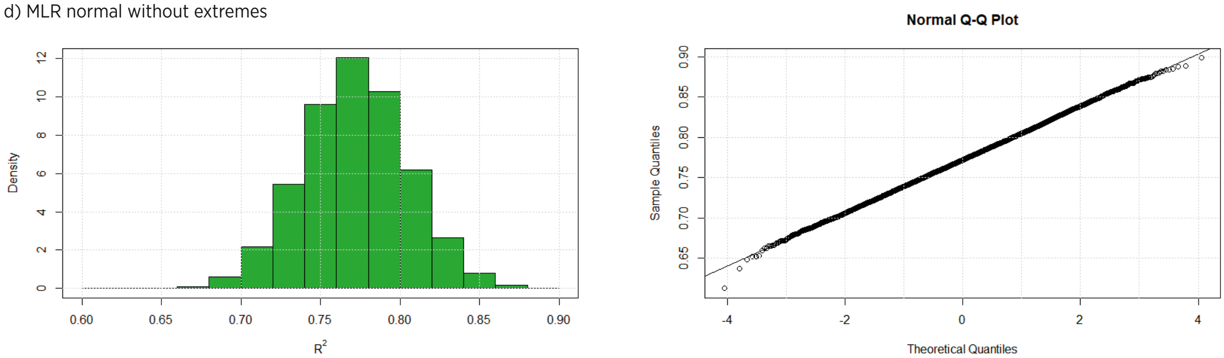
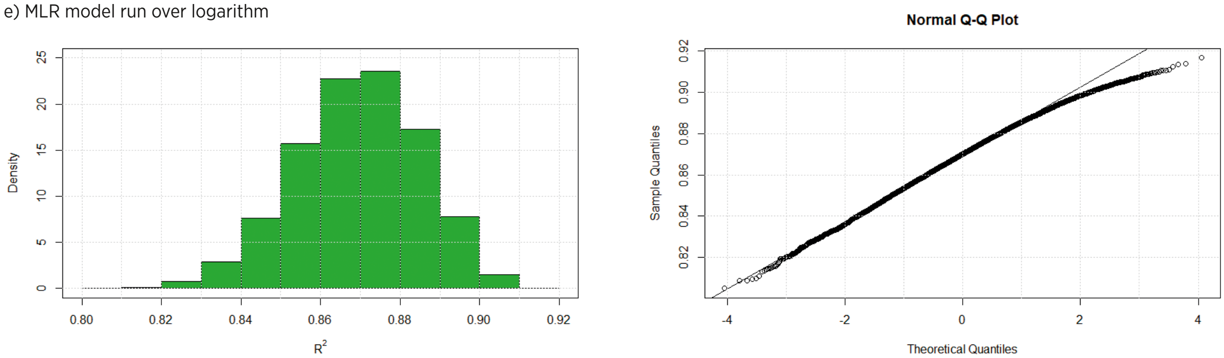


Fig. 9a-c. Distribution of R^2 and Q-Q plots: a) Including extreme data for the ANN model run; b) including extreme data for the ANN model run; c) including extreme data for the MLR model run

d) MLR normal without extremes



e) MLR model run over logarithm



f) MLR model run over logarithm without extremes

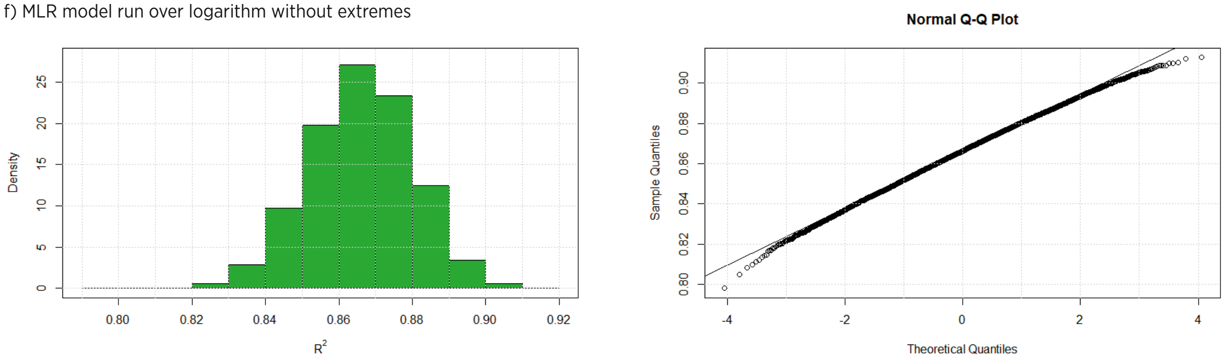


Fig. 9d-f. Distribution of R2 and Q-Q plots: d) without extreme data for the MLR model run; e) including extreme data for the MLR analysis on the dataset run over logarithm; f) without extreme data the MLR analysis on the dataset run over logarithm

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Rainwater harvesting scenarios and its prospective in Pakistan

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ABSTRACT. Water is a precious commodity and water scarcity has become a serious issue in many parts of the world, especially in dense urban areas. Water resources are under increasing stress due to continuous population growth, agricultural development, urbanization, and industrialization. The gap between water demand and supply has also increased in recent years. This has resulted in increasing pressure on underground water resources as well as the depletion of groundwater aquifers at an alarming rate. Thus there is a growing need to explore viable methods and techniques to manage water availability, especially in urban areas. The objective of the current study was to determine the potential for rainwater harvesting (RWH) in the twin cities of Islamabad and Riwalpindi. We evaluated its suitability to supplement the water supply as well as contribute to groundwater recharge and flood control efforts. This could in turn help to overcome water demand, could potentially recharge depleting groundwater resources and could result in the development of a currently untapped additional water source for urban hubs.

KEYWORDS: rainwater harvesting, groundwater recharge, water supply.

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1. INTRODUCTION

Water scarcity is growing in many parts of the world and urban centers are most affected. Water is a major input for the existence of life on the earth. Increased population growth, agricultural expansion, urbanization, and industrialization have resulted in the depletion of available water resources in Pakistan. The gap between water demand and supply has increased rapidly. Surface water shortage impacted nearly 50% of canal supplies during the most recent drought period, which lasted from 1998-2002 (Kahlown, Ashraf 2002). Based on the current population growth rate, there is projected to be a 31% shortage of water in the year 2025, which will increase significantly through 2050 (Sheikh 2017).

The situation is putting pressure on groundwater resources resulting in a continuous draw-down of aquifers, with associated deterioration of water quality. In Islamabad where water supply is generally met from surface storage, 170 public tube wells are also pumping water for domestic and industrial uses. Long-term groundwater data in Islamabad showed an average yearly decline of 0.5 m in the water table (Kahlown, Majeed 2002), a trend which is still continuing (PCRWR 2018).

Thus, the depletion rate of the aquifer has become a major issue associated with the growth of human settlements in big cities. Groundwater exploitation to meet the ever-increasing domestic and industrial water requirements of the cities on a long-term basis requires assurance of a sustainable supply of good quality water (Ariyabandu 1999). Such an assurance cannot be made unless withdrawal of groundwater is replenished under a systemic artificial recharge program (Kharal 2002).

There is a double pronged strategy being followed to manage the water resources of Pakistan: (i) construction of new medium to large reservoirs, and (ii) conservation of water resources through efficient use. There is potential for the construction of medium and large dams in the country, however, this would involve huge investment, national consensus, and above all a considerable investment of time (PCRWR 2018). The other options that can be adopted are appropriate water conservation technologies and the use of non-conventional water resources such as rainwater harvesting.

RWH is defined as the process of collecting natural precipitation from prepared catchments for beneficial use. It is an ancient practice that has been used in various times, in various forms, in most of the world. Allowance of rainwater runoff from the upper reaches and collection at lower reaches is called catchment-based harvesting. This is carried out by storing rainwater from rooftops in small dams or ponds. System design is based on the catchment area, conveyance system, and water storage facility.

Sazakli et al. (2017) conducted a study to assess the 12 Jordanian governorates' residential sectors for potential potable water savings utilizing RWH. They further gave suggestions and recommendations for improving the quality and quantity of RWH. Their findings showed that 5.6% of the total domestic water supply in 2005 was harvested using this technique. Samples Analysis revealed that inorganic compounds in harvested water were in line with WHO standards for drinking purposes. However, the main bacteriological parameters exceeded the drinking water limits (Sazakli et al. 2007).

In Australia, the federal government, along with several states, initiated a regulatory mechanism for water sustainability and took steps to support households buying and setting up systems for RWH that resulted in increased RWH in regional and urban areas of the country. Potential health outcomes of harvested rainwater use were also explored. Trace metals were found to be below the health limit guideline in residential areas, but not in high industrial areas. However, epidemiological evidence suggested no increased risk of gastrointestinal disease from drinking rainwater (Chubaka et al. 2018).

A research survey was carried out for harvested rainwater from buildings in Brazil which considered economic, environmental, and social implications. The authors also assessed the legislation that would be necessary in cities where this practice would be mandated. The survey concluded that there was considerable potential for potable water saving when using rainwater in buildings (Teston et al. 2018).

A research study was initiated to examine the applicability of RWH in urban Zambia. Two peri-urban water stress areas were selected. Mass curve analysis was used to design storage for the system and a rational formula was utilized for designing gutters. Tests of water samples from this system revealed that the water was drinkable (Handia et al. 2003).

Another survey was conducted in Nigeria where climate change is already impacting water supply. Harvested rainwater is the only alternative in this situation. A city with 1,156 mm means annual rainfall was selected. It was found that rainwater could be harvested at a rate of 74.0 m^3 per annum per household. The water demand for laundry and flushing was 21.6 and 29.4 m^3 per annum, respectively. It was concluded that this amount of harvested rainwater could be enough for monthly household water demand for WC flushing and laundry, except for the months of November through February. However, storage of excess rainwater during September and October would be ample to supplement the short fall in drier months. Results showed that potential water savings was highest in June and September (Aladenola, Adeboye 2010).

A research study was started in the UK to compare estimated and actual performance of RWH systems by using calculations and simulation-based approaches (Ward et al. 2012). A RWH system located in an office building was selected for longitudinal empirical performance assessment. The results revealed an average measured water saving efficiency of 87% for an 8-month period because the system was oversized for the actual occupancy level. Thus, a smaller tank could also be utilized for this purpose. Capital payback periods of 11 and 6 years were calculated for the actual over-sized tank and the smaller optimized tank, respectively (Ward et al. 2012).

In Australia, a study was conducted to examine the sustainability of harvested rainwater in multi-story domestic buildings under different scenarios (i.e., varying roof area, floors, water price, and interest rate), in order to categorize suitable conditions where RWH systems prove to be sustainable. A water balance model was developed to calculate water savings for various scenarios. It was found that larger roof area improves water savings and financial benefits. Also, capital, such as plumbing work and maintenance costs, matter for RWH systems. It was found that the financial viability of a RWH system is enhanced by lower interest and increased water price regimes. It was concluded that it would be possible to get "pay back" from this system subject to some suggested scenarios (Rahman et al. 2010).

In the United States, an analysis was done in 23 cities from seven different climatic regions to determine the performance of domestic RWH systems. The considered systems aimed to both improve water supply to residential parcels and to reduce storm water runoff from housing drainage catchments. The results showed that performance is a function of climatic patterns and cistern size. Overall, the results suggested that U.S. cities could get benefits from RWH, both as a means of storm water control and as an alternative source of water (Steffen et al. 2013).

2. WATER SITUATION IN PAKISTAN

The geographical area of Pakistan is 79,610,000 km^2 lying between 30.3753°N and 69.3451°E. Pakistan has an average annual precipitation of around 200 mm, but in northern areas it exceeds 1000 mm. About 50% of rainfall occurs during the monsoon season (July to September). Once a water surplus country having 5,600 m^3 per capita in 1950, Pakistan has turned into a water deficit country with current per capita water availability of nearly 1,000 m^3 (Sheikh 2017). The water resources of Pakistan are under great stress as a result of agricultural and population growth, and associated urbanization and industrialization. Based on the current population growth rate and declining per capita water availability, the gap between water demand and supply is growing rapidly as shown in Figure 1 and further substantiated in Table 1.

2.1. RAINWATER HARVESTING (RWH) POTENTIAL

On the basis of long-term average annual rainfalls, Pakistan has significant potential for RWH from various sources including irrigated areas, rainfed areas, desert areas, coastal areas, and hill torrents as shown in Figure 2. The utilization of this potential water source, with efficient techniques, can help overcome water shortage in the country, as well as help conserve natural resources and ecosystems. In rainfed areas such as Pothwar, the total rainwater potential is about 4.3 billion cubic meter (BCM), out of which only 0.1 BCM is being harvested and utilized. The rest is leaving the area without benefiting the local communities. Similarly, there is great potential in Pakistan for rooftop RWH especially in metropolitan areas. Presently, this is one of the most underutilized approaches to water resource development in the country.

Different research organizations in Pakistan are actively involved in developing techniques and methods for RWH in various parts of the country. These organizations have made significant progress in improving designs for RWH in urban and desert areas, in order to provide drinking water to human populations and livestock, as well as recharge depleting aquifers.

Given the water situation in urban areas, and the need to meet future water demand, research efforts are being focused on expanding RWH techniques in urban areas. For this purpose, the current case study was conducted in the twin cities of Pakistan – Islamabad and Rawalpindi – with the main objective of exploring RWH potential in urban areas.

2.2. RWH POTENTIAL IN TWIN CITIES

Islamabad and Rawalpindi are twin cities with just a highway separating them. Both cities, combined with Taxila and other adjoining areas, form Islamabad/Rawalpindi (Fig. 3).

Islamabad, the federal capital of Pakistan, is spread over an area of 906 km^2, out of which 220 km^2 is urban area. The total population of both cities (Islamabad and Rawalpindi) in 1998 was 0.53 million and 1.4 million, respectively. This has grown to 1.01 million and 2.1 million as per recent cesus of 2017 (GoP 2017). Elevation ranges from 457 m to 1,604 m. Its density is 880 people/km². The water table ranges from 45.72 m to 121.92 m on average but is depleting day-by-day and exploitation of groundwater is becoming comparatively expensive. The major sources of water supply of these cities are Rawal and Simly Lakes. There are several contaminant sources, including hospital waste, poultry waste, and sewerage of catchment areas, which have compromised water quality and safety (PCRWR 2016). Unhygienic water is one of the root causes of disease in the area. Simly and Rawal Lakes are therefore also not cost effective. Islamabad and Rawalpindi are among the few cities in Pakistan that receive per annum precipitation in the range of 950-1,100 mm. The monthly trend based on the long-term record (1961-1990) is evidence of that, as shown in Figure 4.

Rainwater can successfully supplement water supplies in these cities and many other similar areas. This source of water is free from harmful environmental effects and may help in sustainable development. Present water demand is 0.775 MCM per day from Simly and Khanpur Dams. There are an additional 193 tubewells in Islamabad. The maximum water supply capacity to the city is 0.370 MCM per day as shown in Figure 5, and can drop to 0.264 MCM per day, resulting in a shortage to the tune of 0.467 MCM per day.

The normal size of residential plots in Islamabad (Table 2) ranges from 74.32 m^2 to 1,672.26 m^2. The volume of rainwater available for a typical house of 418 m^2 (90% covered areas), with 80% collection efficiency, is given in Table 3, on a monthly and annual basis. The annual water requirement for a family of 6 people, at the rate of 0.1 m^3 per head, is 248.7 m^3. The total available water from a house of 418 m^2 is 319 m^3, this requirement therefore could easily be met from rainwater.

3. GROUNDWATER RECHARGE BY RWH

Generally, about 20% of rainwater percolates into the ground to recharge the aquifer. This percentage is being further reduced in Pakistan by deforestation, increased urbanization, and road and pavement construction, among other causes. In Islamabad, 4.6-6.1 m drawdown occurs every year due to unplanned extractions by the current tube wells in Islamabad and the growth in the number of tube wells in Rawalpindi, as shown in Figure 6 and Figure 7, respectively. This in turn causes:

- short surface supplies, exerting great stress on groundwater resources;
- a continuous increase in groundwater utilization;
- a falling water table in 26 out of 43 canal commands;
- and a continuously declining water table in major cities.

There are several methods of artificial groundwater recharge, including injection wells, ditches, soakways, delay action dams, and leaky dams. It is however, necessary to evaluate the appropriate technologies of RWH in order to rejuvenate depleting fresh water aquifers. The effective implementation of appropriate artificial recharge techniques, in conjunction with RWH, would help sustainable management of groundwater, as well as the water resources of the country as a whole. Depleting aquifers may be recharged by utilizing RWH efficiently by adopting techniques of inverted well or soakways.

3.1. AQUIFER RESTORATION WITH INVERTED WELLS

Inverted wells are essentially pumped wells in reverse as the water enters the aquifer over a small area. Recharge/injection wells are used where the cost of land is very high, such as in urban areas, or the aquifer to be recharged is deep and/or limited. In operation, it is essentially the opposite of groundwater abstraction, thus a recharge mound forms rather than a cone of depression when pumping. These systems are susceptible to clogging by suspended solids in the inject-

Table 1. Water availability and demand in Pakistan (Sheikh 2017)

Year	2004 (BCM)	2025 (BCM)
Water availability (including drinking water)	128	128
Requirement (including drinking water)	142	142
Overall shortfall	11%	31%

Table 2. Plot sizes in Islamabad

Plot sizes in m²									
1,672.26	1,003.35	836.13	551.84	501.68	297.29	227.6	167.23	116.13	74.32

Table 3. Monthly availability of rainwater for a house on an average plot size of 418 m²

Month	Average rain [mm]	% of annual rainfall	Rooftop rainwater [m³]	Total rainwater for a house of 418 m² [m³]
Jan	56.1	4.91	8.70	15.7
Feb	73.5	6.44	11.86	21.3
Mar	89.8	7.86	13.93	25.1
Apr	61.8	5.41	9.58	17.2
May	39.2	3.43	6.10	10.9
Jun	62.2	5.45	9.60	17.3
Jul	267	23.38	41.2	74.1
Aug	310	27.15	48.00	86.5
Sep	98.2	8.60	15.22	27.5
Oct	29.3	2.57	4.54	8.2
Nov	17.8	1.56	2.70	4.9
Dec	37.3	3.27	5.75	10.4
Total	1,142.2	100.00	177.21	319.0

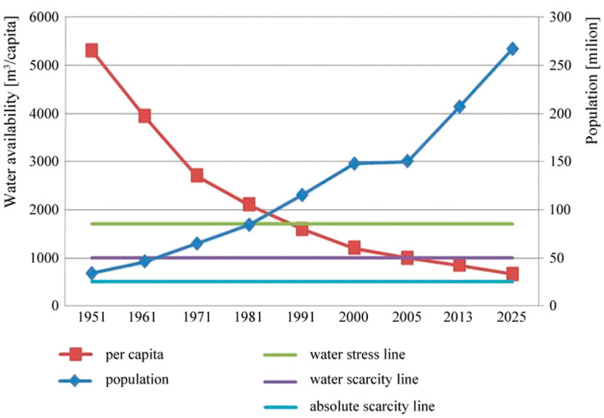

Fig. 1. Population growth vs. non-agricultural water demand (PWP 2000)

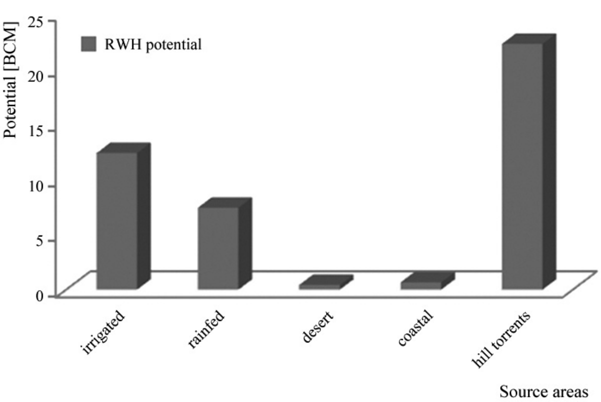

Fig. 2. Pakistan-RWH potential (source: Proceedings of Regional Groundwater Management Seminar, October 9-11.2000 Islamabad)

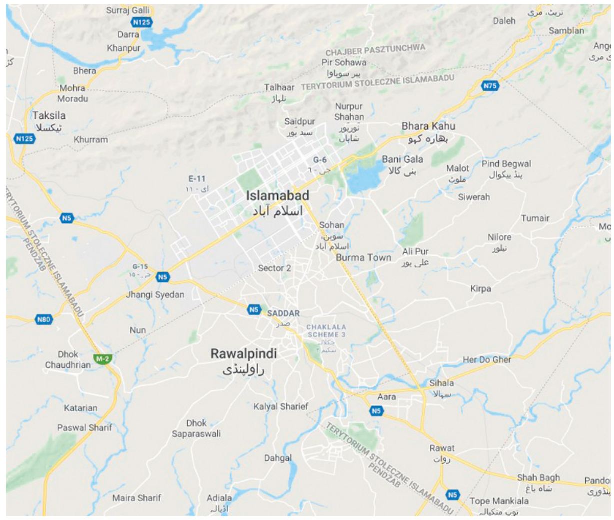

Fig. 3. Combined map of Islamabad and Rawalpindi cities

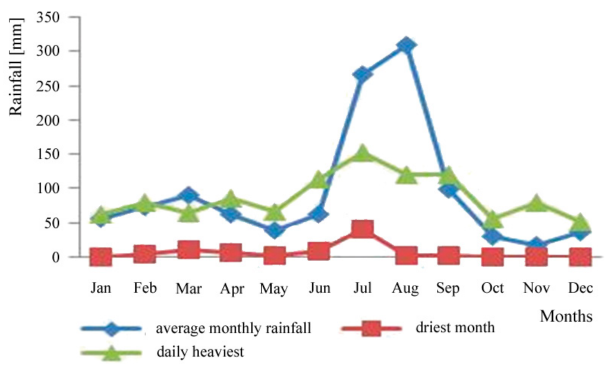

Fig. 4. Monthly average rainfall pattern for Islamabad and Rawalpindi (source: Pakistan Meteorological Department; heaviest rainfall of 23 July 2001 not included)

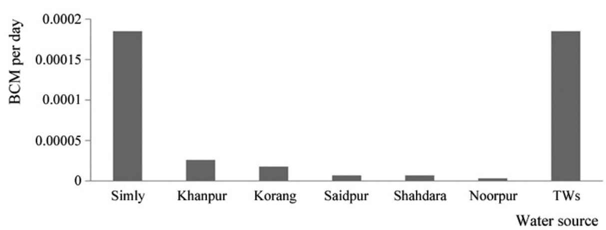

Fig. 5. Daily water supply from various sources to Islamabad (source: Capital Development Authority)

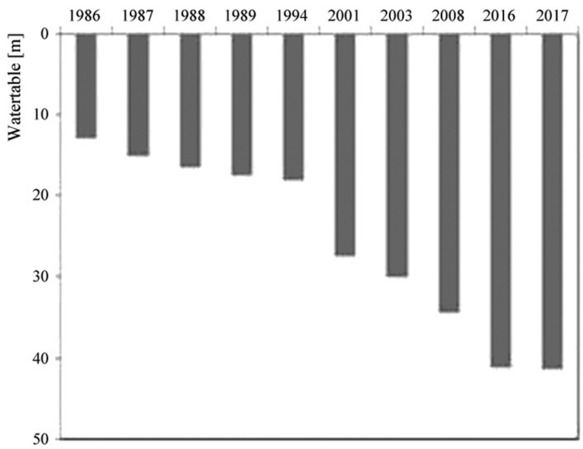

Fig. 6. Yearly trend of ground water depletion in Islamabad (source: PCRWR 2016, 2018)

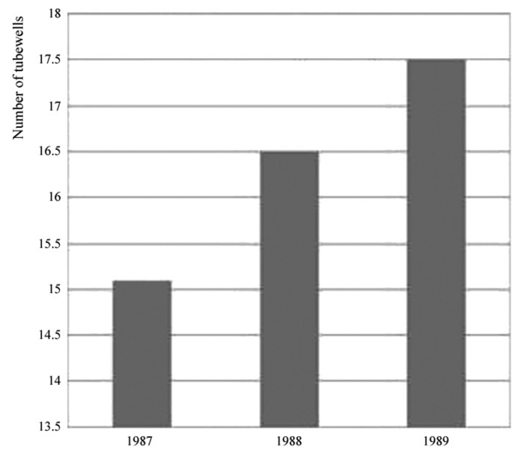

Fig. 7. Yearly trend of tube well increase in Rawalpindi (source: Water and Sanitation Agency, Rawalpindi)

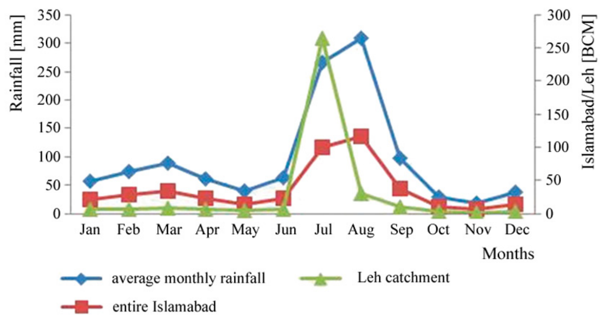

Fig. 8. Surface run-off of Islamabad and Leh catchment area

ed water. Afforestation and vegetative measures in the catchment are necessary to control sedimentation.

3.2. AQUIFER REVIVAL WITH SOAKWAYS

Soakways are another method of artificial groundwater recharge. This method consists of permeable materials located below ground to store runoff, which is utilized for flow to ground water. The permeable surface can be grassed or graveled areas, paving blocks with vertical voids built in, or paving blocks with gaps between individual units. Water is therefore collected from a large surface area, stored in the filter drains, and allowed to infiltrate through the soil. Soakways trap sediments and thereby clean the run-off. It is essential that the surface is kept clear of silt and cleaned regularly to keep the voids clear.

In order to develop the above-defined (3.1 & 3.2) techniques, the catchments of different sites in Islamabad would need to be surveyed for these purposes. Then necessary diversions, if required, would need to be developed to direct rainwater towards the points in the catchment where inverted wells or soakways would be implemented.

3.3. GREEN BELTS FOR GROUNDWATER RECHARGING

Green belts, which are 91.44 meter by 182.88 meter wide, and are positioned astride roads, can be used for easy groundwater recharge as well. Natural depressions in these green belts can store rainwater. By considering an average storage of 100 m × 100 m × 10 m (100,000 cum) per km for 280 km long greenbelts, it would be possible to store 280×100,000 or 28 MCM. As an example, the green belt south of Shaker Parian and sports complex, which is equal to one sector of 2 km by 2 km, would be capable of storing 2000×2000×10, or 40 MCM (Liaqat 2002).

4. RWH FOR FLOOD PREVENTION IN RAWALPINDI

The catchment area of Nullah Leh is 238 km^2, while the Islamabad Territory area is 908 km^2, from which surface runoff is generated during the rainy season. The monthly and total runoff generated in the entire Islamabad and Leh catchment, assuming 50% efficiency, is shown in the Figure 8.

Figure 8 shows about 130.24 MCM of runoff per year is generated by Nullah Leh; this quantity is enough to supply water to Islamabad for one year at the rate of 0.37 million m^3 per day. Capturing and storing rainwater for use is particularly important in dry lands, hilly, urban, and coastal areas. Humans can survive hunger for several weeks if the body possesses sufficient reserves. Lack of water, however, will lead to certain death within days, as the body cannot retain any water reserves. Therefore, we must take stock of the situation and adopt innovative methods and techniques to store and conserve water.

Many countries of the world have realized the importance of RWH and are successfully benefiting from it. Before the situation becomes worse and the minimum water required for essential needs is not available, we must evolve innovative methods of saving water and supplementing our existing water resources by harvesting rainwater. The following recommendations are made with special reference to Rawalpindi and Islamabad.

5. RECOMMENDATIONS/ CONCLUSIONS

a. The annual runoff in the Potohar region is 4.32 BCM, but only a fraction of this is being harvested. Numerous dam sites have been identified in the Islamabad and Rawalpindi area, but in the past several decades, no rainwater storage dams have been constructed in the twin cities. The existing dam sites should be prioritized and new dam sites should also be identified. Construction of new dams should be given top priority in the Annual Development Program and construction of at least one dam per year should be mandatory by each of these two cities.
b. Rooftop RWH must be made obligatory for all citizens of Islamabad and those people of Rawalpindi who live on a plot of 418 m^2 or more. All government buildings must install RWH systems. Construction of RWH systems should be made part of the building bylaws.
c. Subsidies may be given to tenants who adopts RWH techniques via property taxes. In Japan subsidy is given to people to install RWH systems. In Australia special loans are provided by banks for RWH.
d. Penalties may be imposed on residents who dispose of rainwater into storm drainage. In Bon, Germany, households pay a special tax depending upon the amount of storm water they allow into a storm water drain.
e. There is currently no control on the extraction of groundwater and there are no bylaws which restrict or control the pumping out of ground water. It should be compulsory for every agency that extracts groundwater to construct recharging wells in order to recharge the aquifer by harvesting rainwater. The recharging systems should be designed so that the amount of recharge is at least equal to the amount of ground water extracted during the year. Necessary byelaws are needed to restrict extraction of ground water. Concerned agencies should have a record of each tube well in their area and the residential units that have installed water pumps/electric motors to extract ground water.
f. As part of building bylaws, residents should have separate water disposal systems for sewage water and other grey water (e.g., wash basin, kitchen). Sewage water may be drained to a treatment plant for agricultural and irrigation purposes, whereas other water can be used for lower quality water uses.
g. Water charging ponds in open spaces, dams and check dams in nullahs, and distributaries, should be constructed. These ponds will store water for emergency and recharging of ground water. Fatima Jinnah Park and the green belts astride main roads in Islamabad are ideal places to harvest rainwater by making water ponds or recharging wells.
h. The water saving techniques given in this paper are being successfully applied in other countries. We need to encourage our people to use them. All government buildings should have these techniques incorporated into their design and construction.
i. It is a very common sight to see people using high quality municipal water for uses such as watering of lawns or washing cars. Although there are laws to punish the culprits, the fine is so minor that it does not deter people. Municipal laws must be amended and these fines should be increased by a substantial amount.
j. A mass campaign on TV, radio, and print media should be launched to create awareness of RWH, recycling of water, and water saving techniques.

NOTATIONS

RWH – Rainwater harvesting; UNEP – United Nation Environment Program; MCM – Million Cubic Meter; BCM – Billion Cubic Meter; CDA – Capital Development Authority; m^2 – square meter; TV – Television; TW – Tubewell; GoP – Government of Pakistan.

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Application of the commensurability method for long-term forecasting of the highest summer floods on the Danube River at Bratislava

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ABSTRACT. This paper reports the use of the commensurability method for long-term forecasting of the highest summer floods on the Danube River at Bratislava. Bratislava is the capital of the Slovak Republic, as well as its major administrative and industrial centre. In the past, Bratislava has suffered from dangerous floods. The highest floods have occurred most frequently in the summer. Consequently, long-term forecasting of summer floods on the Danube River at Bratislava has important scientific and practical significance. We used the dates of the highest summer floods for the period 1876-2018, as well as historical information about the highest summer floods that occurred before the beginning of regular hydrometric observations. The commensurability method supports prediction of various natural phenomena, including floods and other dangerous events. It is characterized by the simplicity of the calculations and minimum needs for input information. Four methods of forecasting were used: (1) the calculated value of commensurability; (2) the two-dimensional and three-dimensional graphs of commensurability; (3) the time intervals between floods that have occurred in the past; and (4) the number of commensurability equations with three components. The results indicate that the highest summer floods are likely to occur on the Danube at Bratislava in 2020, 2025, and 2030.

KEYWORDS: Flood, long-term forecasting, Weng Wen-Bo method, commensurability.

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1. INTRODUCTION

The Danube River is closely linked to the economic, social, political, and spiritual spheres of public life in 19 European countries, which are wholly or partly located in its basin. It is the water transport artery connecting Central Europe with the Balkans, the Black Sea, and the Middle East (Pekárová et al. 2014). The mechanical energy of the streamflow is converted into electrical energy at 18 hydroelectric stations on the Danube River. The river is also a source of potable and non-potable water for the population, industry, and agriculture of all the Danube countries (Khrystyuk 2013). Despite the many benefits of the river, after heavy rainfall or intensive snowmelt in the basin, catastrophic floods occur periodically, with flooding of densely populated flood plains, leading to property damage and sometimes losses of human lives (Böhm, Wetzel 2006; Romanescu, Stoleriu 2010; Pekárová et al. 2013; Rohr 2013; Sonnlechner et al. 2013; Pekárová et al. 2014; Tenk, Dávid 2015; Blöschl et al. 2016). Therefore, research, modeling, and forecasting of the Danube runoff have scientific and practical importance.

The main or traditional methods of hydrological forecasting are statistical methods, such as correlation and regression analysis, etc., also known as simplified methods. Modern hydrological forecasting often uses a variety of mathematical models (WMO 2009). All these approaches are quantitative methods of forecasting. In general, for the Danube River basin, simplified methods and a stochastic approach have been used for long-term forecasting (for periods exceeding 10 days) (Pekárová et al. 2007; Khrystyuk 2014; Komma et al. 2017; Meissner et al. 2017). However, quantitative hydrological forecasts are not as reliable as they need to be. The development of prognostic systems that would allow accurate and reliable determination of flood hazards is an important, yet difficult task for hydrologic practice (Pekárová et al. 2013; Blöschl et al. 2016).

Along with quantitative forecasting methods, qualitative approaches have been developing (Hongyan et al. 2011; Su, Hu 2015; Peng et al. 2017). One of these approaches is the commensurability method, which the Chinese geophysicist Weng Wen-Bo proposed for long-term forecasting of various natural phenomena (Weng 1984). This method uses the dates on which extreme natural phenomena (earthquakes, floods, droughts, etc.) were observed. For this reason, it has been called the information method. Weng Wen-Bo's method is characterized by simplicity of calculation, graphical visualization, and the use of researcher intuition. The Weng Wen-Bo method was successfully used for forecasting the dates of several large earthquakes in China, Japan, and the USA; wet and dry years in the Songhua River Basin; and the floods in northeast China (Hongyan et al. 2011; Su, Hu 2015; Peng et al. 2017).

The objective of this paper is to use the Weng Wen-Bo information method for long-term forecasting of floods and determination of the most likely years in which these floods will occur on the Danube River at Bratislava.

2. STUDY AREA AND DATA

The Danube is the largest river in Western and Central Europe. The catchment area is 817,000 km^2, and the river's length is 2,857 km. The Danube basin is naturally divided into three parts by mountain ranges: Upper, Middle, and Lower Danube (Fig. 1). The Upper and Middle Danube are separated by the Alps and the Carpathians; the Middle and Lower Danube are separated by the Balkans and the Carpathians. Each major region of the Danube basin is under the influence of specific air masses. The Upper Danube is mainly influenced by the Atlantic and the Mediterranean air masses, the Middle Danube is under the influence of the Atlantic, continental, and Mediterranean

Fig. 1. The Danube River Basin

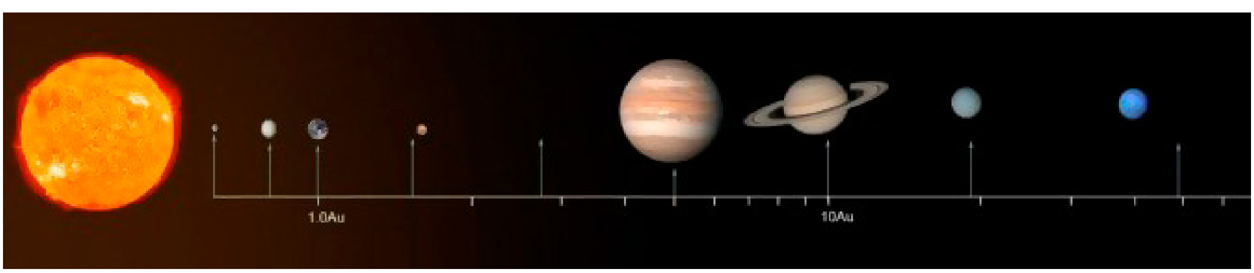

Fig. 2. Illustration of the Titius-Bode Law

air masses, and the Lower Danube is mostly under the influence of continental air masses. The Danube River has a complex hydrological regime because of the varied atmospheric circulation and topographical relief in its basin. The Danube's runoff is formed mainly in its Upper part. In its Middle part additional runoff is contributed by melting snow in the Carpathians and the Balkans, and by rainfall. The Lower Danube is mainly an area of transient flow (Pekárová et al. 2008; Khrystyuk 2013; Pekárová et al. 2014).

Floods are not synchronous between individual parts of the Danube River Basin. Floods occur most frequently in June-August in the Upper Danube River Basin, in April in the Middle part, and April-May in the Lower part. So, depending on timing, the floods can be all water (in summer) or water and ice. In accordance with both archival data and data for the instrumental observation period, the highest floods occurred most frequently in the summer (Pekárová et al. 2014). Therefore, for our investigation, we used observation data from the gauging station at Bratislava, which represents the flood regime of the Upper Danube. This station has a long period of observation, beginning in 1876. For this investigation we used observed data for summer floods from 1876 to 2018.

3. METHODOLOGY

The Danube River runoff has cyclical fluctuations. In our research we have shown that the river and its tributaries are characterized by consistent iteration of the wet and dry phases of cyclical fluctuations (Pekárová et al. 2006; Gorbachova, Khrystyuk 2014; Pekárová et al. 2014; Gorbachova 2015; Zabolotnia et al. 2019). Such fluctuations have different durations. The longer cycles of fluctuations sometimes include less prolonged alternations of wet and dry years. The presence of various cyclic fluctuations is conditioned by the influence of various factors, mechanisms, and principles that can be described by the combined effects of periodic and random factors, as well as by the characteristics of the river basin.

In 1766 the German physicist and mathematician I.D. Titius discovered that the distances of the solar system planets from the Sun (R_n) (Fig. 2) obey a simple empirical rule:

$$R_n = 4 + 3 \cdot 2^n \quad (1)$$

where $n = -\infty$ for the planet Mercury and $n = 0, 1, 2...$ for the next planets.

By studying this astronomical rule, which is also called the Titius-Bode Law, Weng Wen-Bo (1984) suggested that similar order is universal. Thus, various natural phenomena are subject to laws like the Titius-Bode Law. Equation (1) can be written as:

$$\beta = \frac{\Delta R_{n+1}}{\Delta R_n} = \frac{R_{n+1} - R_n}{R_n - R_{n-1}} = \frac{3 \cdot 2^{n+1} - 3 \cdot 2^n}{3 \cdot 2^n - 3 \cdot 2^{n-1}} = 2 \quad (2)$$

where $n = -\infty, 0, 1, 2\ldots$; β is the value of commensurability for the solar system planets.

According to the hypothesis of Weng Wen-Bo, the dates of various natural disasters have a periodicity, which is created by the cosmic influences. Weng Wen-Bo used the term commensurability, which was earlier proposed by Titius. Equation (2) brings to light the law of distribution of matter in a region of space. For the time domain, the commensurability (ΔX) can be expressed as (Su et al. 2016):

$$\Delta X = \frac{X_{i+\Delta i} - X_{i-1}}{K} \quad (3)$$

where K is an integer (1, 2, ...); X_i is an element of the data set. If K is equal to 1, then ΔX is the period of the data set.

For long-term forecasting of extreme natural events the method of Weng Wen-Bo can be used in several ways. We used four methods of forecasting:

1. by the calculated value of commensurability;
2. by the two-dimensional and three-dimensional graph of commensurability;
3. by the time intervals between floods that have occurred in the past;
4. by the number of commensurability equations with three components.

The first method requires calculating the commensurability value from the array of dates on which the extreme events occurred, using equation (3). Forecasts are given in the form of points on the time axis, showing when the next event may occur, taking into account the forecast error.

The second method requires detecting the commensurability values in the array of dates for extreme events and the creation of two- and three-dimensional commensurability graphs.

These graphs are created by considering all possible combinations of values of commensurability.

Final graphics should have the following properties:

- account for the maximum possible observation period;
- include as many dates of extreme events as possible;
- contain periodicity and symmetry vertically and horizontally on two-dimensional graphs and on three sides of three-dimensional graphs;
- have an aesthetic appearance.

Forecasts employ the values of commensurability on the horizontal and vertical axes of the two-dimensional graph and three sides of three-dimensional commensurability graphs.

The third method is to determine the time intervals between the floods that have occurred in the past and the extrapolation of these time intervals for the future. This forecast can be visualized by creating a graph.

For the fourth method we need to draw up the commensurability equations with three components that will indicate the date of the upcoming extreme event:

$$X_i + X_j - X_k = X_l \quad (4)$$

where X_i, X_j, X_k, X_l – the date array of the extreme events; $i, j, k, l = 1, 2, \ldots, n$ – the integers; n – the number of dates in the extreme events array.

Dates that have the largest number of such equations are the dates of a possible extreme event.

4. RESULTS AND DISCUSSION

At Bratislava, regular monitoring of the Danube River runoff began in 1876. During the period 1876-2018, fourteen of the highest summer floods were recorded. The maximum discharges of such floods were more than 8,050 m^3s^{-1} (Table 1). This value corresponds approximately to a discharge of 10% probability ($Q_{10\%}$ = 8,140 m^3s^{-1}).

Forecasting results by the calculated value of commensurability

Applying equation (3), we calculated the commensurability values of the highest summer floods that were observed on the Danube River at Bratislava in the period from 1876 to 2018 (Table 2). The value of commensurability (ΔX) is 2.60 years, the value of K varies in the range 0-13, and the forecast error is ±1 year. The value ΔX was determined by successive approximation, which minimized the error. We have applied the criteria $\Sigma|\text{Error}|$ and $\Sigma(\text{Error})$.

The results of these calculations determine the dates of the possible subsequent highest summer floods on the Danube River at Bratislava (Table 3).

Table 1. The highest summer floods on the Danube River at Bratislava for the period 1876-2018

No.	Year	Discharge [m^3s^{-1}]	No.	Year	Discharge [m^3s^{-1}]
1	1883	9,062	8	1965	9,224
2	1890	8,548	9	1975	8,715
3	1892	8,380	10	1991	9,430
4	1897	10,140	11	2002	10,370
5	1899	10,870	12	2009	8,242
6	1920	8,616	13	2010	8,071
7	1954	10,400	14	2013	10,640

Table 2. Commensurability of the highest summer floods on the Danube River at Bratislava in the period from 1876 to 2018

No.	Years (X_i)	(X_i – X_{i-1})	K	K*ΔX	Error:(X_i – X_{i-1}) – K*ΔX
1	1883				
2	1890	7	3	8	-1 (–0.8)
3	1892	2	1	3	–1 (–0.6)
4	1897	5	2	5	0 (–0.2)
5	1899	2	1	3	–1 (–0.6)
6	1920	21	8	21	0 (0.2)
7	1954	34	13	34	0 (0.2)
8	1965	11	4	10	1 (0.6)
9	1975	10	4	10	0 (–0.4)
10	1991	16	6	16	0 (0.4)
11	2002	11	4	10	1 (0.6)
12	2009	7	3	8	–1 (–0.8)
13	2010	1	0	0	1 (1.0)
14	2013	3	1	3	0 (0.4)

Σ|Error| = 6.8
Σ(Error) = 0.0

Table 3. Possible dates of the highest summer floods on the Danube River at Bratislava

No.	K	K*ΔX	Date of the possible highest flood: 2013 + K*ΔX
1	3	8	2021
2	4	10	2023
3	5	13	2026
4	6	15	2029
5	7	18	2031

Table 4. Dates of the highest summer floods that occurred in the past on the Danube at Bratislava

No.	K	K*ΔX	Date that was calculated by value of commen-surability: 1883 + K*ΔX	Date from historical archives (Pekárová et al. 2014)	Error
1	–259	–673	1210	1210	0
2	–207	–538	1345	1344	–1
3	–185	–481	1402	1402	0
4	–160	–416	1467	1466	–1
5	–151	–393	1490	1490	0
6	–148	–385	1498	1499	1
7	–147	–382	1501	1501	0
8	–137	–356	1527	1526	–1
9	–111	–289	1594	1594	0
10	–82	–213	1670	1670	0
11	–77	–200	1683	1682	–1
12	–37	–96	1787	1787	0

Table 5. The total number of time intervals of different duration indicating the date of the possible future highest summer flood on the Danube at Bratislava

No.	Year	Number of time intervals	No.	Year	Number of time intervals
1	2019	8	8	2026	4
2	2020	18	9	2027	4
3	2021	8	10	2028	7
4	2022	5	11	2029	7
5	2023	7	12	2030	9
6	2024	6	13	2031	5
7	2025	9			

1899	55	**1954**	55	**2009**
21		21		21
1920	55	**1975**	55	**2030**
34		34		
1954	55	**2009**		

Fig. 3. The two-dimensional graph of commensurability of the highest summer floods on the Danube at Bratislava

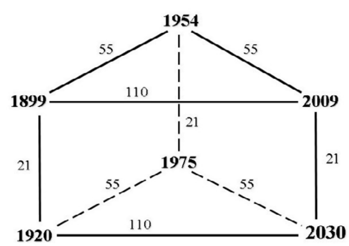

Fig. 4. The three-dimensional graph of commensurability of the highest summer floods on the Danube at Bratislava

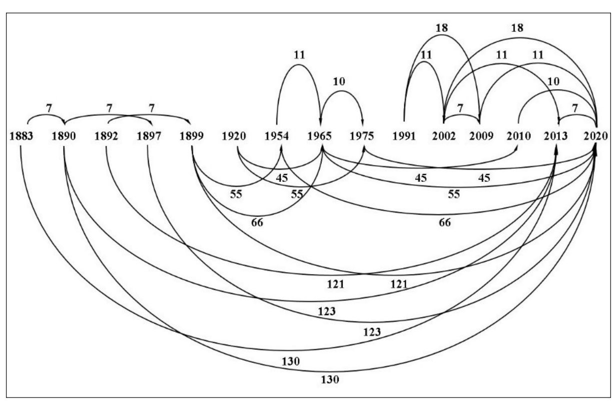

Fig. 5. Butterfly structure diagram of the highest summer floods on the Danube River at Bratislava (2020 is a forecast)

Table 6. Time intervals that are indicating a possible high summer flood on the Danube at Bratislava in 2020

No.	Time interval, years		Number of repetitions
1	7	1890 – 1883 = **7** 1897 – 1890 = **7** 1899 – 1892 = **7** 2009 – 2002 = **7** **2020 – 2013 = 7**	4
2	10	1975 – 1965 = **10** **2020 – 2010 = 10**	1
3	11	1965 – 1954 = **11** 2002 – 1991 = **11** 2013 – 2002 = **11** **2020 – 2009 = 11**	3
4	18	2009 – 1991 = **18** 2020 – 2002 = **18**	1
5	45	1965 – 1920 = **45** 2010 – 1965 = **45** 2020 – 1975 = **45**	2
6	55	1954 – 1899 = **55** 1975 – 1920 = **55** 2009 – 1954 = **55** **2020 – 1965 = 55**	3
7	66	1965 – 1899 = **66** **2020 – 1954 = 66**	1
8	121	2013 – 1892 = **121** **2020 – 1899 = 121**	1
9	123	2013 – 1890 = **123** **2020 – 1897 = 123**	1
10	130	2013 – 1883 = **130** **2020 – 1890 = 130**	1

Table 7. Time intervals that indicate a possible high summer flood on the Danube at Bratislava in 2025

No.	Time interval, years		Number of repetitions
1	16	1899 – 1883 = **16** 1991 – 1975 = **16** **2025 – 2009 = 16**	2
2	23	1920 – 1897 = **23** **2025 – 2002 = 23**	1
3	34	1954 – 1920 = **34** 2009 – 1975 = **34** **2025 – 1991 = 34**	2
4	71	1954 – 1883 = **71** 1991 – 1920 = **71** **2025 – 1954 = 71**	2
5	105	2002 – 1897 = **105** **2025 – 1920 = 105**	1
6	126	2009 – 1883 = **126** **2025 – 1899 = 126**	1

74

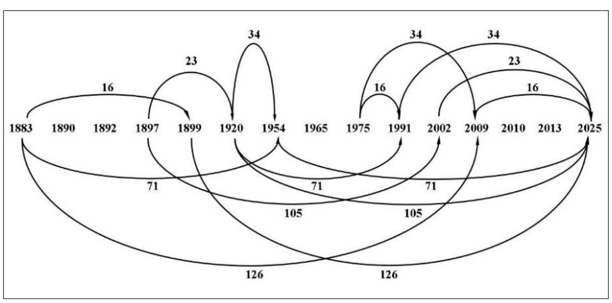

Fig. 6. Butterfly structure diagram of the highest summer floods on the Danube River at Bratislava (2025 is a forecast)

Table 8. Time intervals that indicate a possible high summer flood on the Danube at Bratislava in 2030

No.	Time interval, years		Number of repetitions
1	21	1920 – 1899 = **21** 1975 – 1954 = **21** **2030 – 2009 = 21**	2
2	28	1920 – 1892 = **28** **2030 – 2002 = 28**	1
3	55	1954 – 1899 = **55** 1975 – 1920 = **55** 2009 – 1954 = **55** **2030 – 1975 = 55**	3
4	76	1975 – 1899 = **76** **2030 – 1954 = 76**	1
5	110	2002 – 1892 = **110** 2009 – 1899 = **110** **2030 – 1920 = 110**	2

Table 9. Number of commensurability equations with three components for the dates of possible high summer floods on the Danube at Bratislava for the period 2019-2031

Year	Number of equations
2019	4
2020	**9**
2021	4
2022	3
2023	4
2024	4
2025	**5**
2026	2
2027	3
2028	4
2029	**5**
2030	**5**
2031	4

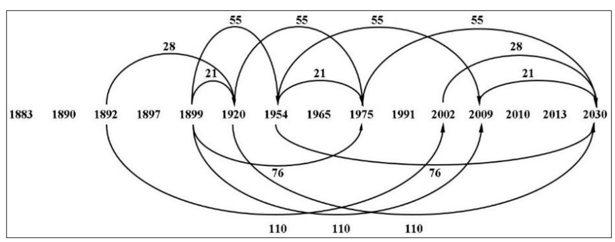

Fig. 7. Butterfly structure diagram of the highest summer floods on the Danube River at Bratislava (2030 is a forecast)

Table 10. The commensurability equations with the three components for the dates of possible high summer floods on the Danube at Bratislava: 2020, 2025, 2029, and 2030

Year	Equations
2020	1890 + 2013 – 1883 = **2020** 1887 + 2013 – 1890 = **2020** 1899 + 2013 – 1892 = **2020** 1954 + 1965 – 1899 = **2020** 1965 + 1975 – 1920 = **2020** 1965 + 2009 – 1954 = **2020** 1975 + 2010 – 1965 = **2020** 2002 + 2009 – 1991 = **2020** 2009 + 2013 – 2002 = **2020**
2025	1954 + 1954 – 1883 = **2025** 1899 + 2009 – 1883 = **2025** 1920 + 2002 – 1897 = **2025** 1954 + 1991 – 1920 = **2025** 1991 + 2009 – 1975 = **2025**
2029	1899 + 2013 – 1883 = **2029** 1954 + 1965 – 1890 = **2029** 2002 + 2002 – 1975 = **2029** 1991 + 2013 – 1975 = **2029** 2010 + 2010 – 1991 = **2029**
2030	1920 + 2002 – 1892 = **2030** 1954 + 1975 – 1899 = **2030** 1920 + 2009 – 1899 = **2030** 1975 + 1975 – 1920 = **2030** 1975 + 2009 – 1954 = **2030**

The value of commensurability (ΔX = 2.60 years) can be used not only to predict the dates of the future highest summer floods, but also to determine the dates on which such floods occurred in the past on the Danube at Bratislava. The analysis shows that the dates of the highest summer floods from historical archives (Pekárová et al. 2014), which occurred before regular hydrometric observations, are closely consistent with the dates calculated using the value of commensurability (Table 4).

Forecasting results by the two-dimensional and three-dimensional graph of commensurability

Analyzing the date array of the highest summer floods, we found that the time intervals between individual floods were the same values: 1954 – 1899 = **55**; 1975 – 1920 = **55**; 2009 – 1954 = **55** and 1920 – 1899 = **21**; 1975 – 1954 = **21**; and 1954 – 1920 = **34**; 2009 – 1975 = **34**. This information supplies the two-dimensional graph of commensurability of the highest summer floods on the Danube at Bratislava (Fig. 3).

According to this graph, we can predict the following highest summer flood: vertically 2009 + 21 = 2030 and horizontally 1975 + 55 = 2030. We also created the three-dimensional graph, which also shows that the highest summer flood can occur in 2030 (Fig. 4).

Forecasting results by the time intervals between floods that have occurred in the past

The time intervals between the individual highest summer floods that occurred in the past (1876-2013) were determined. We extrapolated these time intervals for the future to determine the dates of the highest summer floods that may occur in the coming years (2019-2036) (Table 5). We did not use dates of flood events before the regular monitoring because we are not sure that all the dates of high summer floods for the period 1210-1883 were identified in the historical archives.

The largest time span, namely 18 years, indicates that a high summer flood may occur in 2020 (Table 5, Fig. 5). In the past the time interval of 7 years has been repeated four times, time intervals of 11 and 55 years, three times, and time interval wof 45 years, twice (Table 6).

Nine intervals indicate a possible high summer flood in 2025 (Table 5, Fig. 6). Time intervals of 16, 34 and 71 years have been repeated twice in the past (Table 7).

A high summer flood may also occur in 2030 (and nine intervals also indicate this) (Table 5, Fig. 7). In the past the time interval of 55 years has been repeated three times, and the time intervals of 21 and 110 years were repeated twice (Table 8).

Forecasting results by the number of commensurability equations with the three components

For the period 2019-2031, we have created all possible commensurability equations with three components, using the dates of the highest summer floods that have occurred in the past (1876-2018) on the Danube at Bratislava.

The largest number of equations (9) with three components was compiled for 2020 (Table 9). Consequently, the next high summer flood on the Danube at Bratislava may occur in 2020. Also, high summer floods are possible in 2025, 2029 and 2030. For these dates, 5 equations were compiled (Table 9).

The application of the commensurability method supported forecasts of the possible dates of high summer floods on the Danube at Bratislava. Although our results are tentative, it can be argued that they can be reliable. This confidence is reinforced by the application of the four commensurability forecasting methods, as well as by the retrospective analysis based on historical data. Strong consistency can be seen between historical flood dates that occurred before the beginning of regular hydrometric observations, and dates that were calculated by the values of commensurability. Thus, commensurability reflects the laws determining the occurrence of high floods as well as other natural disasters. The methodological approach of Weng Wen-Bo may be applicable to forecasting other dangerous natural phenomena, thus meriting further in-depth research.

Long-term forecasting of possible dangerous spring floods can be used to prevent and minimize the negative effects for the population and economy.

5. CONCLUSION

Weng Wen-Bo's methodology is perhaps the only one that supports long-term forecasting of various natural disasters, including floods, with the minimum array of input information. After calculating the commensurability value for the highest summer historical floods, we forecast possible high summer floods on the Danube at Bratislava in the coming years: 2021, 2023, 2026, 2029 and 2031. Retrospective analysis of the calculated commensurability value confirmed the dates of the highest summer floods that occurred in the past.

The two- and three-dimensional graphs of the commensurability clearly indicate that a high summer flood may occur in 2030 on the Danube at Bratislava. The method of forecasting by the time intervals between the highest summer historical floods shows that high summer floods may possibly occur in 2020, 2025 and 2030. The forecasting method using the number of commensurability equations with three components shows the dates of possible high floods in 2020, 2025, 2029, and 2030.

So, the majority of commensurability methods indicate to us that the next series of high summer floods on the Danube at Bratislava may occur in 2020, 2025, and 2030.

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Influence of a lake on river water thermal regime: a case study of Lake Sławianowskie and the Kocunia River (Pomeranian Lakeland, Northern Poland)

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ABSTRACT. Water temperature is one of the basic physical parameters of rivers and lakes. Rising temperature can transform these ecosystems over a broad range of factors (water mixing, water quality, biological conditions, etc.). In the case of rivers, their thermal regimes also can be modified by local conditions (e.g., tree cover, adjoining water bodies, etc.). In this paper, we address the functioning of the river-lake system in northern Poland (Kocunia River-Lake Sławianowskie) in terms of the effect of the lake on temperature conditions in the river. Dependencies in daily water temperatures between stations located above and below the lake were assessed with linear regression. Based on daily morning water temperatures for the period 2012-2017, it was determined that water temperature in the river below the lake was higher than at the measurement site located above the lake by an average of 1.1°C. The greatest differences were recorded in summer-autumn months when average monthly downstream water temperatures were as much as 3.9°C higher than upstream water temperatures. This phenomenon is an example of a local factor (the lake) magnifying global factors, i.e. rising temperatures associated with climate change. The information in this paper can provide future reference for decision makers and state institutions with responsibility for measures aimed at reducing the effects of climate change.

KEYWORDS: River-lake system, water temperature, measurement data.

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1. INTRODUCTION

Lakes are important elements of the natural environment, shaping its character both in their direct vicinity and throughout their catchments (affecting the hydrological conditions, microclimate, etc.). They are landscape-forming elements, and guarantee biodiversity (Ptak et al. 2013). Due to their strong ability to accumulate energy and matter, the presence of lakes contributes to the mitigation of extreme hydrological situations (droughts and floods, among others). Direct relationships between lentic and lotic waters are evident where lake deltas form, as exemplified by Lake Płociczno (Chudzikiewicz et al. 1979), among others. Lakes also fulfill important roles in the transport of various dissolved and particulate substances as they circulate in the catchment. The accumulation of materials in lake sediments can change properties of the river above and below the lake. Such a situation is referred to by Hillbricht-Ilkowska (2005), among others, in the case of the functioning of river-lake systems in northeast Poland. Temperature is one of the basic physical properties of surface waters. This parameter largely determines the functioning of many lake and river ecosystems. The occurrence, course, and scale of many processes (e.g., duration of the ice season, water mixing, solubility of different kinds of substances, etc.) have strong correlations with water temperature. Water temperature is a fundamental element of hydrobiological conditions. The diversity of the flora and fauna, the abundance within species, and where and when they occur depend on the thermal regime.

One of the most serious problems faced by humanity today is climate change (Nowak, Ptak 2018; Nowak, Ptak 2019; Ptak et al. 2018; Ptak et al. 2019b). In this context, it seems important to reduce greenhouse gases, thus inhibiting further increases in air temperature. Such action will inhibit transformations of all other closely related components of the natural environment (including water temperature). At the global scale, such measures require international arrangements, which are not always possible in the current geopolitical environment. Therefore, it is important to determine local factors that can affect thermal conditions of surface waters (Ptak 2018).

This paper addresses the assessment of Lake Sławianowskie's impacts on the thermal conditions of the Kocunia River in northern Poland.

2. MATERIALS AND METHODS

Thermal conditions were analysed in the Kocunia River, which flows through Lake Sławianowskie in the Pomeranian Lakeland in northern Poland (Fig. 1). The length of the river segment analysed is 41 km; its catchment area is 171 km^2. This section of the river is characterised by a low gradient. Its channel width does not exceed several meters, and depth varies, depending on the hydrological situation, from 12 to several tens of centimetres (Fig. 2). The morphological parameters of Lake Sławianowskie are as follows: surface area 277.6 ha,

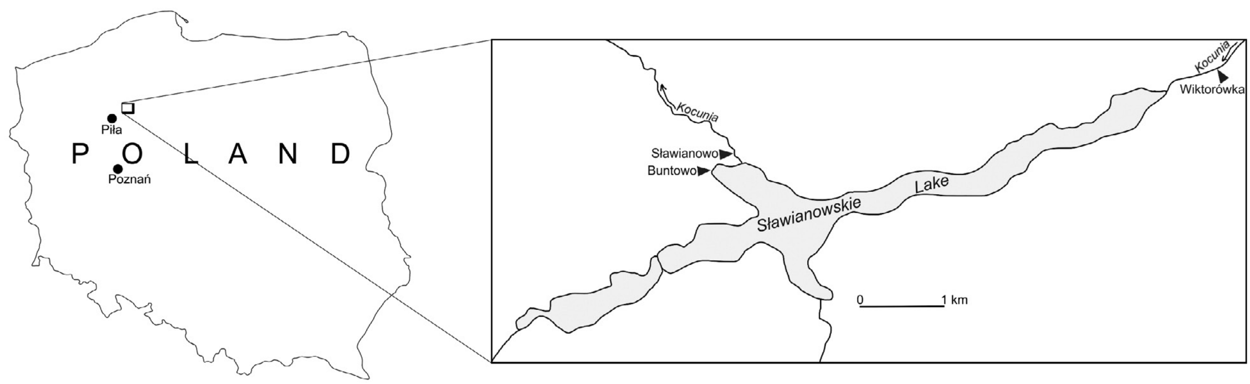

Fig. 1. Location of study object

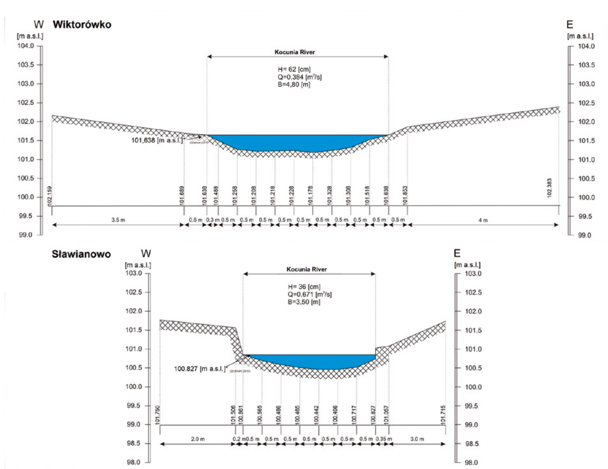

Fig. 2. Cross-sections through the Kocunia River channel in profiles at Wiktorówko and Sławianowo performed on 22.01.2015 (based on data from IMWM-NRI)

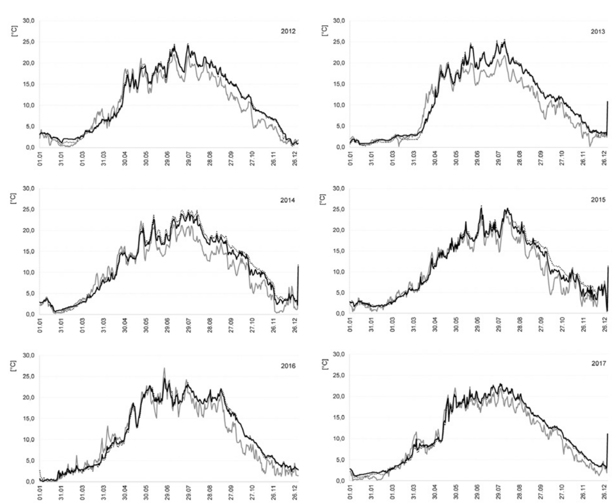

Fig. 3. Time series of water temperature in Lake Sławianowskie (dotted line), the Kocunia River at the inflow to the lake (grey line), and at the outflow from the lake (black line) in the years 2012-2017 (based on data of IMWM-NRI)

water volume 18.3 million m^3, maximum depth 5.0 m, mean depth 6.6 m. The lake, with the characteristics of a channel, is composed of two basins separated by narrows with a bridge crossing. The western basin is smaller, shallow, and strongly overgrown with rushes. The eastern basin is strongly elongated, deeper, and includes two bays reaching north and south, so that the lake resembles a cross (Fig. 1). The inflow of the Kocunia River to the lake is located at its eastern end; the outflow is at the end of the northern bay. The lake is surrounded by a narrow belt of a mixed tree stand, and further by extensive agricultural land (WIOS 2003).

Water temperature was measured at three water gauge stations of the Institute of Meteorology and Water Management, National Research Institute (IMWM-NRI). Two of the gauges (Wiktorówko and Sławianowo) are located on the Kocunia River (500 m above the lake and 160 m below the lake, respectively), and one (Buntowo) is located on the northern part of the lake (Fig. 1). The measurement series covered calendar years 2012-2017. The measurements were performed at 6.00 AM by means of an OTT Orpheus Mini Water Level Logger at the river stations, and by an observer at the lake station. Measurement sensors were located in the vicinity of water gauges in limnometric columns. The sensors were immersed at a depth of 40 cm from the water surface. Data readout and device operation control took place once a month.

Air temperature used in this study was taken from the synoptic station of IMWM-NRI in Piła, approximately 30 km south of the study area. The measurements were carried out manually in a meteorological cage at a height of 2 m above the surface. Relationships between water temperatures at the three stations were examined with linear regression and R software (*lm* function) (Daròczi 2015).

3. RESULTS

Among the three sites of water temperature measurement, the site at the inflow to the lake showed a pattern different from the others (Fig. 3 and 4). This contrast is associated with the course of the Kocunia River through Lake Sławianowskie, which causes transformation of the physical parameters of water carried by the river (including water temperature, among others) into those characteristics of the lake. In the multi-annual period of our analysis, average annual differences in water temperature in the Kocunia River above and below Lake Sławianowskie varied from 0.9 to 1.4°C (Fig. 4). Over a multiyear monthly scale, average differences in water temperature varied from –1.3 to 2.7°C (Table 1). On a monthly scale, average differences in water temperature varied from –2.6 in April 2013 to 3.9°C in August 2014 (Table 1).

Analysis of the comparisons in Table 1, along with the course of variability of daily temperatures in the river and lake (Fig. 3), indicates a two-fold character of the dynamics of water temperature in the Kocunia River measured above and below Lake Sławianowskie over an annual cycle. The smallest differences are recorded in winter and spring months when they do not exceed 1.3°C; from January to March they are less than 0.5°C (Fig. 4). In the colder half of the year, water temperature frequently depends on the occurrence of ice (both in the river and lake). When ice is present, there are smaller thermal contrasts between stations under both lentic and lotic flow conditions. It is also important that during spring, temperatures at the outflow are lower than at the inflow to the lake (Figs. 4 and 5). In the summer-autumn months, in most cases (almost 70%), average monthly differences between outflow and inflow temperatures are higher than 2.0°C (in the extreme case, August 2016, the difference reached 3.9°C (Table 1). In summer, water in the near-surface layer of Lake Sławianowskie is heated faster than that in the Kocunia River above the inflow to the lake. The river temperature is influenced by its sources, i.e. surface runoff and groundwater. According to Chomutowska and Wilamowski (2014), river water temperature changes very fast in comparison to still waters (lakes, ponds), depending on air temperature, groundwater temperature, and springs feeding the river, among other factors. Above the first measurement site (approximately 0.6 km), there is a strongly overgrown flow-through lake with an area of 5 ha. Water flowing through the shaded surface of the lake is subject to a slower heating process. A similar situation is described by Bielak (2014), among others, referring to swamps overgrown with reed beds around Biebrza, participating in the alimentation of the river. Alimentation with (colder) groundwater is important during summer, when water resources in the catchment are successively exhausted.

Water temperatures in Kocunia at the Wiktorówko and Sławianowo stations were strongly correlated (0.92 and 0.88, respectively) with air temperature (station Piła). The correlations suggest that air temperature plays the key role in the thermal regime of the river, although it is lower in the case of the station below the outflow from Lake Sławianowskie (Sławianowo). In this context, the calculated correlation between surface temperature in Lake Sławianowskie and the observation site on Kocunia located below it was almost perfect: 0.997 (r^2 = 0.994) (Fig. 6). This tight correlation reflects the fact that water flowing in the river 160 m below the lake still shows properties of lake waters in terms of temperature.

Temperature measurements (2012-2017) in the Kocunia River at the inflow to Lake Sławianowskie (Wiktorówka), and at the outflow (Sławianowo), were compared using a linear regression analysis. The results confirmed the dependence of the outflow temperature (explained variable) on the inflow temperature (explanatory variable) at a level of significance of <0.001. The regression equation was y = 0.74 + 1.04 x, where y is the outflow temperature and x the inflow temperature (r^2 = 0.945, p = 2.2·10^{-16}). This result suggests that water temperature in the Kocunia River is higher at the outflow from Lake Sławianowskie than at the inflow.

4. DISCUSSION

The issue of thermal relationships between lentic and lotic waters has been frequently addressed in the context of reservoirs (Poirel et al. 2010; Maheu et al. 2016; Wiejaczka, Wesoly 2017; Jiang et al. 2018). Deep water reservoirs with a bottom outlet cause an increase in water temperature in rivers in winter, and a decrease in summer (Olden, Naiman 2010). Different patterns apply to shallow reservoirs: during the warm months, an increase in water temperature in rivers below dams is observed (Lessard, Hayes 2003). Differences in water temperature in Julianpolka in southern Poland were determined by Wiatkowski (2008), where temperature was higher by an average of 2.4°C at the site below the reservoir. Łaszewski (2015), analysing the effect of reservoirs on the temperature of the Jeziorka and Rządza Rivers (vicinity of Warsaw) in the summer season, determined that there was a considerable increase in average monthly values below the reservoirs. In the case of Lubrzanka (Świętokrzyskie Mountains, southern Poland), significant differences were observed throughout the study period between water temperature above and below the existing reservoir (Kozłowski 2017). Water in the river below the weir was on average 3.2°C higher than above the reservoir, and the great-

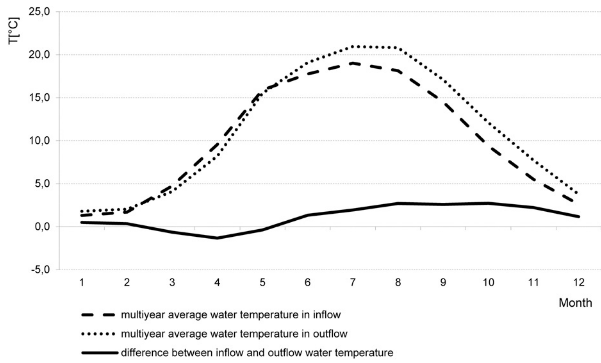

Fig. 4. Multiyear monthly average water temperature of the Kocunia River at the inflow and outflow of Lake Sławianowskie 2012-2017 (based on data of IMWM-NRI)

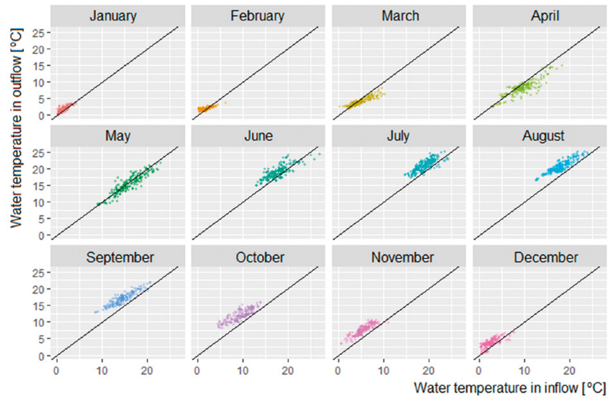

Fig. 5. The relationship between the inflow and outflow of water temperature of Lake Sławianowskie for each month during the period 2012-2017

Table 1. Average monthly differences in water temperature [°C] in the Kocunia River between stations located at the outflow and inflow from the lake (based on data of IMWM-NRI)

Month	Year						Average
	2012	2013	2014	2015	2016	2017	
January	0.8	−0.1	0.4	0.5	0.3	1.0	0.5
February	1.1	−0.1	0.0	0.3	−0.2	1.0	0.3
March	−1.1	0.5	−1.2	−0.7	−0.9	−0.5	−0.6
April	−1.2	−2.6	−1.4	−0.9	−1.5	−0.5	−1.3
May	−0.2	−0.3	0.1	−0.4	−0.5	−1.0	−0.4
June	1.7	2.4	2.0	0.8	0.6	0.6	1.3
July	2.2	3.2	2.4	1.5	0.4	1.8	1.9
August	2.4	3.5	3.9	2.1	1.9	2.3	2.7
September	2.7	3.2	2.7	2.2	3.0	1.7	2.6
October	2.9	2.4	2.7	3.2	3.4	1.7	2.7
November	2.3	2.6	2.6	1.4	2.6	2.0	2.2
December	1.0	1.4	1.3	0.8	1.1	1.3	1.2
Average	1.2	1.4	1.3	0.9	0.9	0.9	1.1

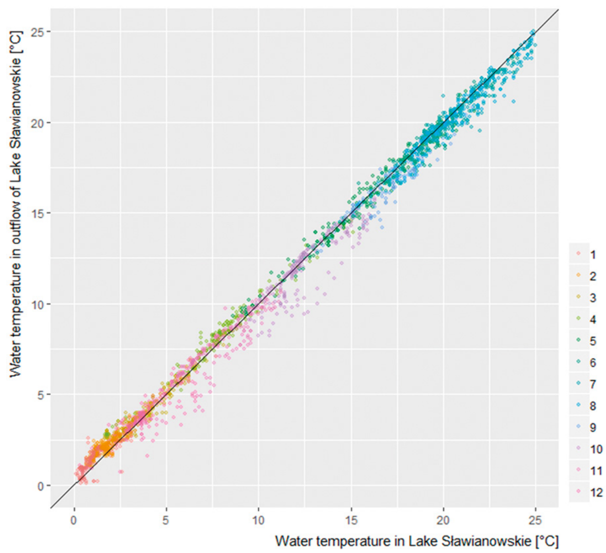

Fig. 6. The relationship between the surface and outflow water temperature of Lake Sławianowskie by month during 2012-2017

est difference in temperature (4.3°C) was recorded in August. According to the study, water temperature in the river below the weir in each of the analysed months was higher below the reservoir than above it.

The results reported here are consistent with the studies summarized above. Although the lake we studied has no typical polymictic parameters, i.e. thermal variability observed in the deepest place of the lake in the summer season (Fig. 7), the hypolimnion is thin, and the zone with the greatest depth (more than 10 m) occupies only about 25% of the lake volume (Choiński et al. 2013). Due to the shallow depth of the Kocunia channel at the outflow from the lake (Fig. 2), water from the near-surface zone, usually heated to a greater degree than the deeper parts of the lake, is discharged first.

This study corresponds with the global research trend, popular over recent decades (Ptak, Nowak 2016; Ptak et al. 2018; Martinsen et al. 2019; Ptak et al. 2019a; Zhu et al. 2019), concerning the thermal conditions of surface waters, both lotic and lentic. In a broader context, it is also related to the course of ice phenomena on rivers and lakes. The great majority of the numerous studies analysing thermal conditions of surface waters (Hampton et al. 2008; Schneider, Hook 2010; O'Reilly et al. 2015) points to changes in thermal regimes, and particularly increases in water temperature. These changes apply in Poland, where average temperature in 14 lakes increased by 0.43°C·dec^{-1} over the past four decades (Ptak et al. 2018). In the case of rivers outside mountainous areas, an increase from 0.17 to 0.27°C was observed (Marszelewski, Pius 2016). In the zone directly adjacent to the Baltic Sea, the warming varied from 0.26°C·dec^{-1} to 0.31°C·dec^{-1} (Ptak et al. 2016). Moreover, the duration and extent of ice cover on rivers has declined (Ptak, Choiński 2016; Choiński et al. 2015; Nowak et al. 2018). These dynamics point to the complexity of potential consequences of changes in thermal conditions of flowing waters, which will intensify over the next several decades (Czernecki, Ptak 2018). Detailed monitoring of the thermal regime of surface waters should be undertaken, along with measures aimed at slowing the heating of lake waters, as postulated by Ptak et al. (2018), among others. In documented cases, such measures could involve a change in the land use structure in the catchments or direct vicinity of rivers. Forested riparian zones and a high percentage of forest cover in catchments can contribute to lower water temperatures, as documented by Ptak (2017), among others, in the case of two rivers in southern Poland.

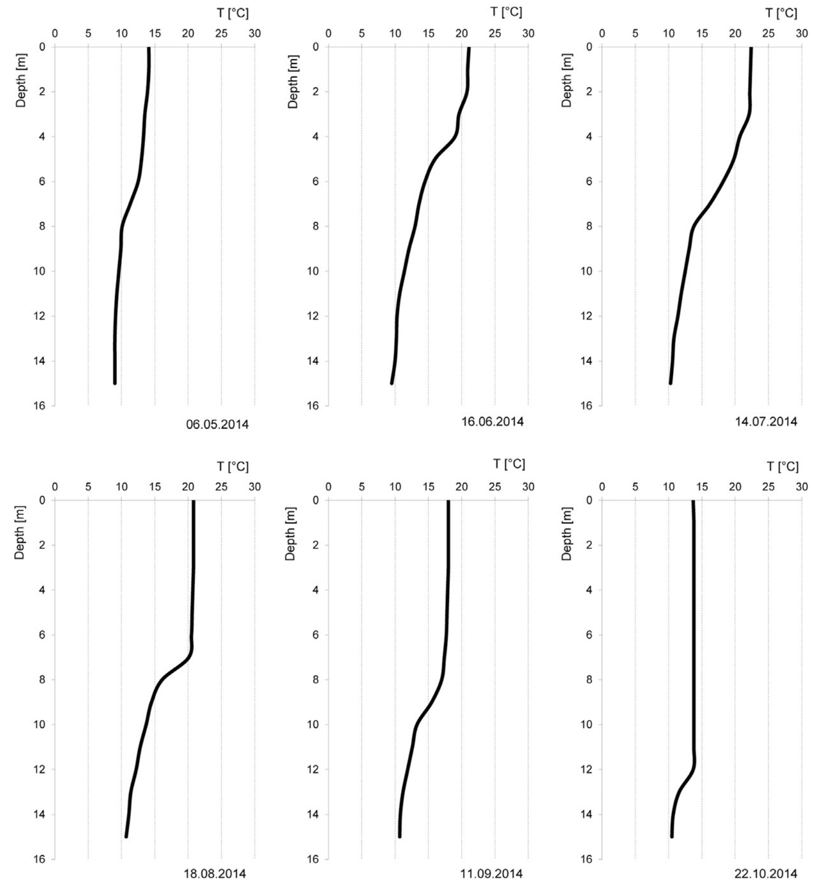

Fig. 7. Example thermal profiles in Lake Sławianowskie in the warm half of the year 2014 (based on data from IMWM-NRI)

5. CONCLUSIONS

We analysed water temperature in the Kocunia River-Lake Slawianowskie system. The observations showed that the lake affects the thermal regime of the Kocunia River by increasing its water temperature below the lake for most of the year (Fig. 4). Only in the period from February to May are the water temperatures at the lake outflow slightly lower than the water temperatures at the lake inflow. Differences between the measurement sites on the river located above and below the lake in the multi-annual period show that below the lake, average annual water temperature was higher by an average of 1.5°C. In the monthly cycle, the greatest differences occur in summer and autumn months, particularly in September and October, when on average they exceeded 4.0°C multiple times. The study corresponds with other studies showing that artificial shallow-water reservoirs increase temperatures in rivers flowing through the reservoirs (Lessard, Hayes 2003; Wiatkowski 2008; Łaszewski 2015). In this study, the same role was observed in the case of a natural lake with developed thermal stratification. The local dynamics of water temperature need to be considered in the context that they intensify the global factors that cause increasing air temperature and consequently, water temperature. Information included in this paper can provide the basis for future reference for persons or state authorities responsible for measures aimed at the reduction of effects of climate change.

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The interaction between local factors and the Convectively Coupled Equatorial Waves over Indonesia during the Western North Pacific and Australian monsoon phase

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ABSTRACT. A large scale perturbation by the Convectively Coupled Equatorial Waves (CCEW) is often observed in the tropics as a precursor to influence weather condition, for example over the Indonesian archipelago (Maritime Continent (MC)). This study examines the interaction between local factors and CCEW with regard to convection and vertical interferences on a local scale over Indonesia during extreme Western North Pacific (WNP) and Australian (AU) monsoon phases. Through space-time spectra analysis of a 15 year (2001-2015) Tropical Rainfall Measuring Mission (TRMM) 3B42 dataset, the propagation of CCEW, i.e. Kelvin, Equatorial Rossby (ER) and Mixing Rossby-Gravity (MRG) waves was assessed. An Empirical Orthogonal Function (EOF) 1 and 2 for each wave evolution across the region of Indonesia, was then compared with daily precipitation anomalies and multilevel wind observations from seven locations in Indonesia to assess the interaction between local factors and CCEW. Results suggest there is evidence of local convection associated with Kelvin waves in the afternoon through to the evening in Tangerang, Surabaya and Makassar during WNP monsoon phases. Local convection associated with MRG waves only occurred in Makassar at the last evolution day during the same period, while there is no clear evidence for an interaction between local factors for ER waves. Low-level westerly winds appear to be significantly coupled with convection from Kelvin waves in Tangerang, Surabaya, and Makassar during the WNP monsoon phase, while the interaction is less significant for MRG-coupled convections (except in Makassar during the same monsoon phase) and absent for ER waves. This study suggests that the global scale phenomena of the Kelvin wave is associated with local scale factors in controlling convection, particularly during an extreme WNP phase in Indonesia.

KEYWORDS: Convectively Coupled Equatorial Waves, Kelvin wave, local factor, monsoon, Indonesia.

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1. INTRODUCTION

Since its discovery by Yanai and Maruyama (1996), tropical equatorial waves have emerged as a popular research topic when investigating the significant drivers of regional weather dynamics (Liebmann, Hendon 1990; Takayabu, Nitta 1993; Wheeler, Kiladis 1999; Lubis, Jacobi 2014). Further study linked this phenomenon with convective activity (Wheeler, Kiladis 1999), described as Convectively Coupled Equatorial Waves (CCEW). Using space-time spectra analysis (hereafter referred to as WK99) to filter long periods of time series data, each type of wave can be distinguished by its wavenumber and frequency; i.e. Kelvin, Equatorial Rossby (ER), Mixing Rossby Gravity Wave (MRG), and Inertia Gravity (IG). When a wave is coupled with convection, CCEW can modulate rainfall variability in the tropics, particularly over the Maritime Continent (MC) of Indonesia (Wheeler, McBride 2005; Kiladis et al. 2009; Horinouchi 2012; Lubis, Jacobi 2014). Furthermore, the Asian-Australian monsoon plays a significant role for CCEW behavior over the MC, as it can intensify and shift the impacted area latitudinally (parallel to the equator) (Wheeler, McBride 2005; Kiladis et al. 2009; Horinouchi 2012; Lubis, Jacobi 2014). Additional interactions between the Madden-Julian Oscillation (MJO) and CCEW over the MC, as well as local factors such as regional terrain complexity cause further complicate regional rainfall variability and weather patterns (Kikuchi et al. 2017).

The aim of this study is to investigate the contribution of local factors in comparison with convective and vertical influences at a local scale, to help constrain global CCEW phenomena during the Asian and Australian monsoon phase over Indonesia. In this study, the Asian monsoon phase, represented by the Western North Pacific (WNP) monsoon, and the Australian (AU) monsoon phase are defined by the global rainfall monsoon domains described by Wang et al. (2012) (Fig. 1).

2. DATA AND METHODS

The Tropical Rainfall Measuring Mission (TRMM) 3B42 version 7 (V7) is a combined precipitation estimation from multiple satellites which has been proven as an adequate proxy for precipitation for tropical areas related to the Asian-Australian monsoon (Giarno et al. 2018). The daily precipitation from a 15-year dataset (2001-2015) of 3B42 was used to filter Kelvin, ER, and MRG waves using space-time spectra analysis WK99. This method transforms a space-time 3B42 dataset into a wavenumber-frequency form, which then filters each wave based on each specific wavenumber and frequency domain according to each wave characteristic (Wheeler, Kiladis 1999). Using a 30 year 850 hPa zonal wind dataset (1986-2015) from the ERA-Interim reanalysis, days of extreme monsoon activity were identified, based on the expected variability characterized by the WNP and AU monsoon indices from Wang and Fan (1999) and Yim et al (2013). WNP and AU indices were calculated by averaging low-level zonal wind; WNP index was from U850 (5°N – 15°N, 100°E – 130°E) – U850 (20°N – 35°N, 110°E – 140°E), whereas AU index was calculated from U850 (0°S – 15°S, 90°E – 130°E) – U850 (20°S – 30°S, 100°E – 140°E). The days with extreme WNP and AU monsoon indices were collated to define the three months with the most extreme monsoon index over Indonesia. Since monsoon phases are commonly referred to by the season with prevailing winds (cf. Ramage 1971) rather than by its peak monsoon index, the WNP monsoon phase will be referred to as December-January-February (DJF), while the AU monsoon phase will be referred to as July-August-September (JAS).

Adapted from the method of Zhao et al. (2013), an Empirical Orthogonal Function (EOF) mode 1 and 2 was applied to each filtered wave to determine its evolution stage, obtained using a lag-regression method. Furthermore, significant CCEW in the 3B42 dataset were identified using Principal Component (PC) 1 and 2 above the standard deviation. Days of both significant CCEW and extreme WNP and AU monsoon activity were then collated to form a group of days with extreme WNP and AU monsoon phase related to CCEW. Through spatial analysis of these groups of data from EOF 1 and 2, the mode with the most similar wave variance was identified, where Kelvin was represented by EOF 2, while ER and MRG were represented by EOF1. Through this method, the evolution stage of CCEW related to extreme NWP and AU monsoon phases was obtained.

Furthermore, using a 30 year (1986-2015) observation dataset of daily precipitation from seven stations (Fig. 2), normal rainfall variability was determined. Using 3 hour time-steps, precipitation anomalies outside of this normal variability which occurred in WNP and AU monsoon phases in the same dataset during the most recent 15 years (2001-2015) were then plotted for each wave evolution stage related to CCEW, to represent the local precipitation characteristic in the seven locations over Indonesia (Fig. 2). Additionally, days with an average of 12-hourly multi-level winds which occurred within the same period, as observed from sounding stations within similar locations, were plotted to demonstrate local atmospheric dynamics related to CCEW. This multi-level wind dataset was obtained from the Indonesian Agency of Meteorology Climatology and Geophysics (BMKG).

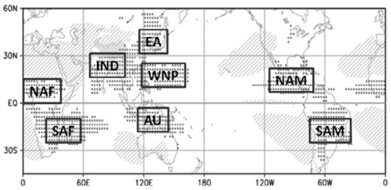

Fig. 1. Regional precipitation domains defined and abbreviated by Wang et al. (2012); this study focusses on the Western North Pacific (WNP) and Australian (AU) monsoon phases

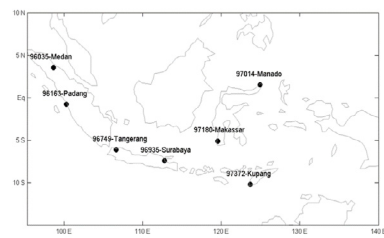

Fig. 2. Observational sounding stations from the Indonesian Agency of Meteorology Climatology and Geophysics (BMKG) dataset, identified by WMO number and city name

3. RESULTS AND DISCUSSION

The spatial distribution of each CCEW evolution stage is overlaid with the average daily precipitation in Figures 3, 4 and 5 (for Kelvin, ER, and MRG waves, respectively). These figures indicate that precipitation generally follows the location of the wave perturbation, particularly for Kelvin waves (Wheeler and McBride 2005). Figure 3 also shows a strong link between a positive Kelvin wave and heavy precipitation over the Indonesian region during both extreme monsoon phases. Therefore suggesting that Kelvin waves are adequate to control weather conditions in Indonesia during an extreme WNP and AU monsoon phase. Meanwhile, ER waves appear to be less vigorous than Kelvin and display unorganized disturbance patterns, presumably due to its off-equatorial impact (cf. Matsuno 1966; Kiladis, Wheeler 1995; Kiladis et al. 2009; Lubis, Jacobi 2014), where maximum perturbations occur in regions to the north and south of the equatorial line, but still within tropical latitudinal boundaries. Although the effect of ER waves is less strong than Kelvin, there are some positive ER signals that could potentially be associated with the intensification of precipitation in Indonesia during both extreme monsoon phases, particularly over Papua at day –4 during DJF and over western offshore of South Sumatra at day 0 during JAS. Meanwhile, lower magnitude perturbations of MRG waves were observed over Indonesia compared to Kelvin and ER, in line with the previous study of Kiladis et al. (2009), therefore indicating that MRG waves are inadequate to evoke extreme precipitation over

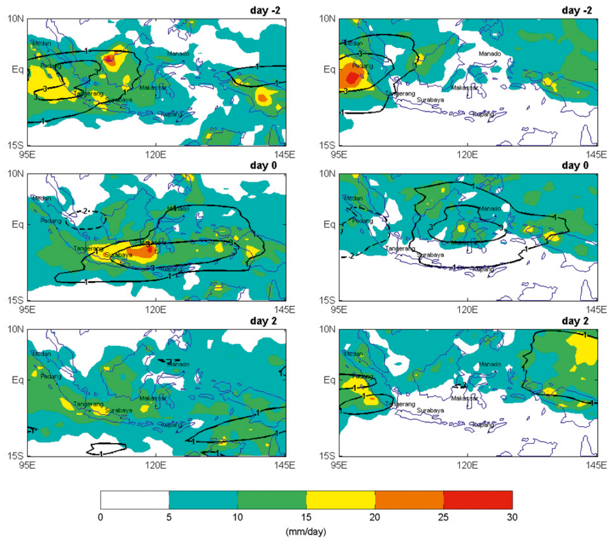

Fig. 3. Day −2 through day +2 lags of Kelvin wave propagation associated with daily precipitation rate (colored shades; mm/day). Kelvin wave propagation is represented by EOF2 using lag-correlation of EOF1 and 2 from 15-year Kelvin-filtered TRMM-3B42 (solid black contour lines for positive and dashed black contour lines for negative), for DJF-WNP (left) and JAS-AU (right) monsoon phase over Indonesia

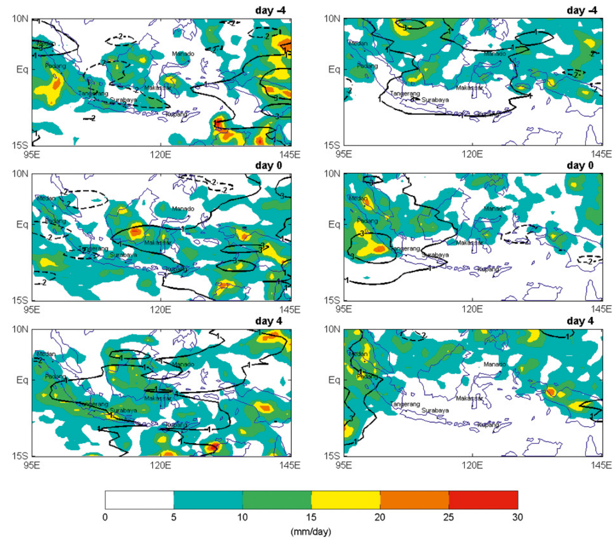

Fig. 4. Day −4 through day +4 lags of ER wave propagation associated with daily precipitation rate (colored shades; mm/day). ER wave propagation is represented by EOF1 using lag-correlation of EOF1 and 2 from 15-year Kelvin-filtered TRMM-3B42 (solid black contour lines for positive and dashed black contour lines for negative), for DJF-WNP (left) and JAS-AU (right) monsoon phase over Indonesia

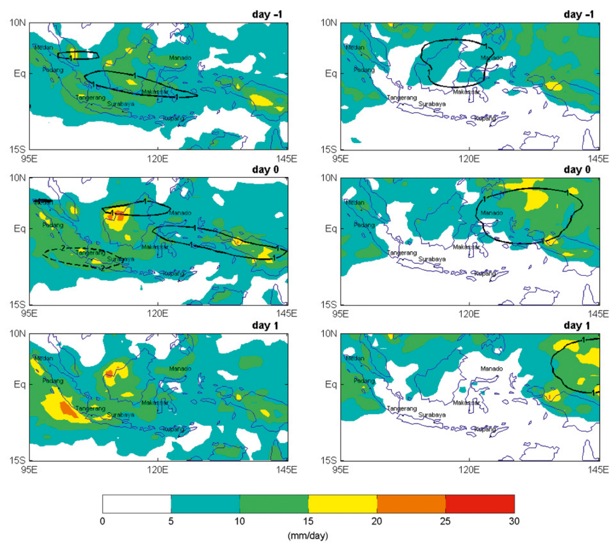

Fig. 5. Day −1 through day +1 lags of MRG wave propagation associated with daily precipitation rate (colored shades; mm/day); MRG wave propagation is represented by EOF1 using lag-correlation of EOF1 and 2 from 15-year Kelvin-filtered TRMM-3B42 (solid black contour lines for positive and dashed black contour lines for negative), for DJF-WNP (left) and JAS-AU (right) monsoon phase over Indonesia

this region. However, considerable precipitation which overlaps with positive MRG perturbation from day 0 to day 1 over Kalimantan and Papua during DJF, confirms that MRG waves contribute to intensifying convection, even though the impact on precipitation is less significant compared with Kelvin and ER waves.

Even though there is a northward and southward shift in precipitation as a result of solar insolation during an extreme AU and WNP monsoon phase, the areas affected are still limited regions near the equator as a result of the dynamic constraints around the equatorial line (Wheeler, Kiladis, 1999). However, Kelvin and MRG waves were more confined to equatorial regions (cf. Matsuno 1966; Gill 1982) compared with ER waves which extended further latitudinally into the northern and southern hemisphere. Moreover, there is a slight discrepancy in the latitudinal distribution between an extreme DJF-WNP and JAS-AU monsoon phases, where the extent of DJF appears to be closer to the equator (Indonesia-Malaysia region) than JAS which spreads northward. This pattern is presumably caused by the increased abundance of water vapor over the Indonesia-Malaysia region during DJF which is absent during JAS (Ramage 1971), enhancing convection significantly over equatorial MC during DJF. Further examination is needed to clarify this relationship.

Figure 6, 7 and 8 show a diurnal cycle (with 3 hour time-steps) of precipitation anomalies for each wave evolution stage during WNP and AU monsoon phases (as in Fig. 3-5). Positive precipitation anomalies, particularly during day 0 (Fig. 6; left), suggests a positive feedback of Kelvin waves on local precipitation in Indonesia during

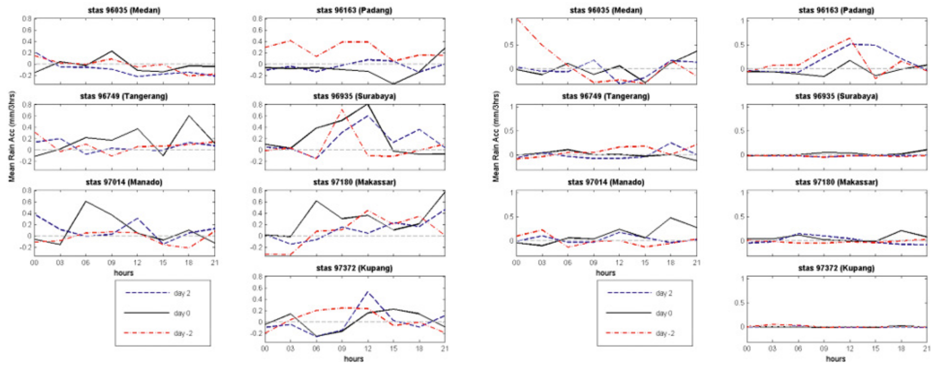

Fig. 6. A 3-hourly (time in UTC) precipitation rate related to Kelvin wave propagation for each day lags (see legend) at seven observation stations as shown in Figure 2, for DJF (left) and JAS (right)

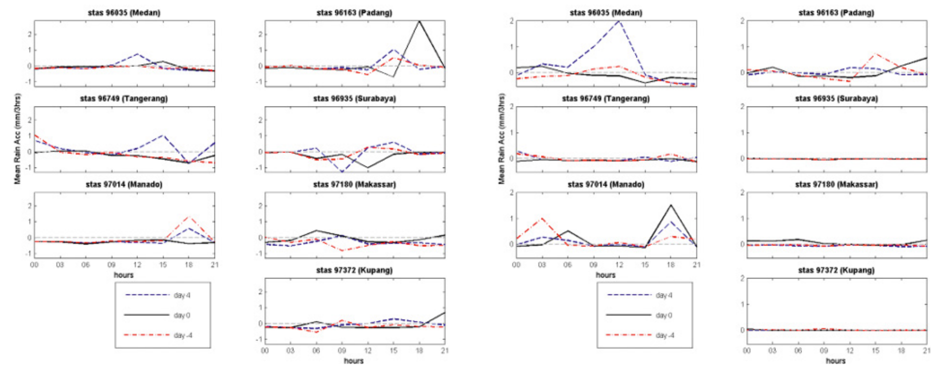

Fig. 7. A 3-hourly (time in UTC) precipitation rate related to ER wave propagation for each day lags (see legend) at seven observation stations as shown in Figure 2, for DJF (left) and JAS (right)

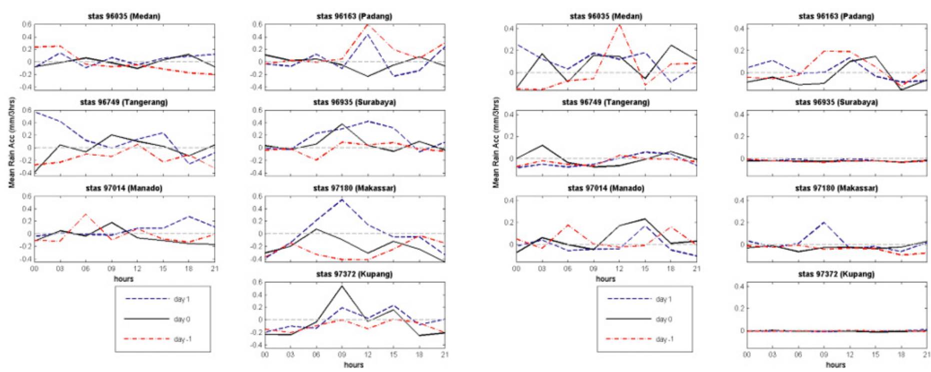

Fig. 8. A 3-hourly (time in UTC) precipitation rate related to MRG wave propagation for each day lags (see legend) at seven observation stations as shown in Figure 2, for DJF (left) and JAS (right)

DJF, except in Medan, Padang, and Kupang. This could be as result of the propagation of the Kelvin wave, where it reaches Medan and Padang at day –2 and Kupang at day +2. A clear sky in the morning (00-03Z) exhibited in Tangerang, Surabaya, Manado, and Makassar later showed intensified rain during the afternoon (06Z) and through to the subsequent early morning (21Z), indicating a strong local convection coupled with a Kelvin wave over these locations during DJF. On the other hand, a slight positive local precipitation anomaly at all stations except Medan, Padang, and Manado, follows the positive perturbation area of the Kelvin wave during JAS (Fig. 6; right). A clear morning sky was only observed in Padang during the whole study period, with similarly clear skies at Manado at day 0 and in the afternoon at Medan seems to be clear during the afternoon. Rain was observed at Medan from the early morning up to early afternoon for almost all the intervals during JAS. However, a lack of significant positive anomaly on day 0 for those three locations during JAS reveals that the connection between Kelvin waves and local factors are dominant during WNP monsoon phase, rather than during AU monsoon phase over Indonesia.

Meanwhile, a predominant negative local precipitation anomaly at day 0 coincides with ER wave propagation during DJF and a slightly positive anomaly at day 0 during JAS (Fig. 7), indicating there is no connection between local factors and ER

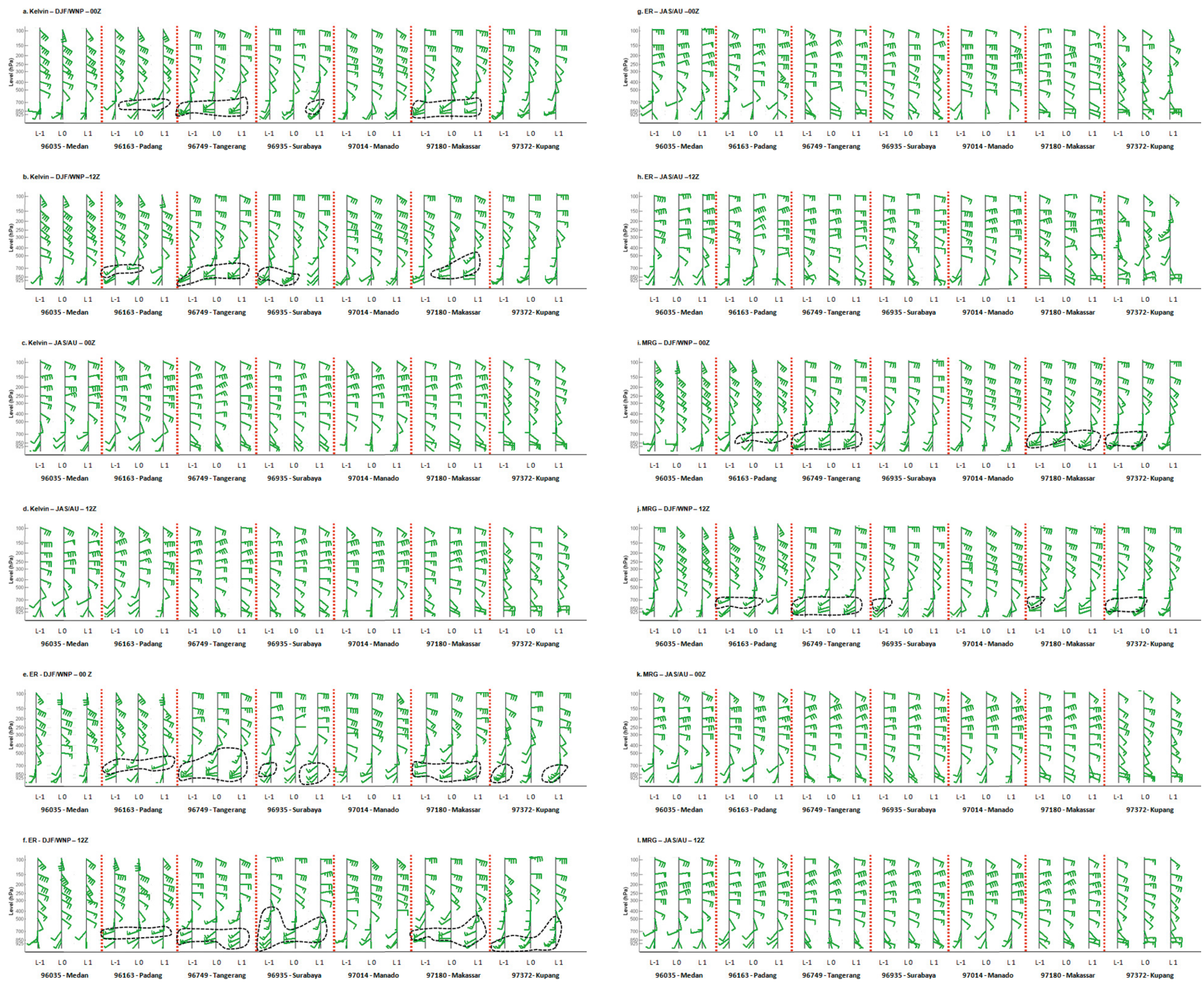

Fig. 9. Multi-level wind profiles from seven observation stations as shown in Figure 2; each lag (characterized by the hPA range on the horizontal axis) refers to the day lag for each wave, as depicted in Figure 3-8; Kelvin waves are plotted for DJF-WNP monsoon phase at 00Z (a) and at 12Z (b) and for JAS-AU monsoon phase at 00Z (c) and at 12Z (d); ER wave are plotted for DJF-WNP monsoon phase at 00Z (e) and at 12Z (f) and for JAS-AU monsoon phase at 00Z (g) and at 12Z (h); MRG waves are plotted for DJF-WNP monsoon phase at 00Z (i) and at 12Z (j) and for JAS-AU monsoon phase at 00Z (k) and at 12Z (l); note that significant multilevel wind at >20 knots for the DJF-WNP monsoon phase and >10 knots for the JAS-ASU monsoon phase are indicated by a dashed black contour lines

waves during both monsoon phases. The distinctive significant positive anomaly which occurred in Padang during DJF, as well as anomalies in Medan and Manado during JAS can be discounted due to its incoherency with the positive perturbation area (Fig. 4). Overall, results suggest there is no local-ER connection over Indonesia related to an extreme WNP and AU monsoon phase.

A lower rate of local precipitation is shown for MRG waves for both WNP and AU monsoon phases (Fig. 8), compared with those of Kelvin and ER waves. However, a peak positive anomaly in Makassar at day +1 during DJF, and in Manado at day 0 during JAS, coincides with the positive MRG perturbation area (Fig. 5), which confirms a relationship between local factors and MRG waves, even though anomalies are less extreme (cf. Horinouchi 2012). At these two locations, convective rains occur during the afternoon (09Z) and evening (15Z) for Makassar during DJF and Manado during JAS, respectively. An apparent positive anomaly at other locations could be disregarded due to their inconsistency with MRG positive perturbations (Fig. 5). Hence, similar to ER waves, there is a less significant link between MRG waves and local factors which regulate convection over Indonesia, with exceptions in Makassar during the WNP monsoon phase and in Manado during the AU monsoon phase.

Local atmospheric dynamics exhibits only a slight divergence in wind direction between the morning (00Z) and the evening (12Z) (Fig. 9). Thus, climatological multi-level wind is primarily controlled by global scale phenomena rather than a local scale factors which exhibit daily variability.

From Figure 9 (a-l), significant (>10 knots) low-level (up to 700 hPa) westerly winds are observed during the WNP monsoon phase for almost all locations, while a lower magnitude of westerly wind remains only over the western part of Indonesia during the AU monsoon phase. Figure 9 (a-d) indicates that low-level westerly winds that are particularly apparent during DJF follow significant precipitation patterns within Kelvin wave envelopes (see Fig. 3), which is in agreement with the previous finding of Yang et al. (2006). Tangerang, Surabaya and Makassar exhibit significant low-level westerly winds which coincide with significant precipitation during the WNP monsoon phase. Even though there is quite a strong westerly wind during DFJ over Padang at 00 and 12 Z, the convection cluster and Kelvin positive perturbation area do not follow this condition. An absence of significant westerly wind during JAS, except in Padang where a weak westerly wind follows convection, indicates local factors have little impact on vertical interferences for Kelvin waves at almost all locations in Indonesia during the AU monsoon phase.

Unlike Kelvin waves, a significant westerly wind observed over almost all locations during DJF indicates a weak connection between ER waves and local factors, due to the inconsistency in rainfall anomalies (Fig. 7). A strong westerly wind during DJF and easterly wind during JAS reveals that the monsoon controls weather conditions in Indonesia (Ramage 1971) rather than ER waves. The other reason is due to its off-equatorial center, which drives the ER signal away from the near-equatorial regions (cf. Kiladis, Wheeler 1995; Lubis, Jacobi 2014). With the exception of a significant westerly wind which is coupled with a positive local precipitation anomaly and an MRG wave (Fig. 8) in Makassar at day +1 during DJF, there is a lack of significant connection at almost all other locations, indicating that there is a less significant connection between local factors and MRG waves over almost all of Indonesia, as previously suggested by Kiladis et al. (2009).

4. SUMMARY

The connection between local factors and CCEW, particularly the contribution of local factors on CCEW behavior in the MC region has been assessed in this study. Significant precipitation which is linked to Kelvin wave propagation, suggests that this type of CCEW profoundly controls the weather conditions in Indonesia, particularly during DJF, compared with ER and MRG waves. This is supported by local convection during the afternoon and through to the evening in Tangerang, Surabaya and Makassar, which is linked to Kelvin wave propagation during an extreme WNP monsoon phase. The only exception to this occurs at Makassar, where local convection is associated with an MRG wave at day +1 during an extreme WNP monsoon phase.

Furthermore, low-level westerly winds associated with convection within CCEW envelopes are significant for Kelvin waves during an extreme WNP monsoon phase, while absent for ER and MRG waves, with the exception of the MRG wave in Makassar during an extreme WNP monsoon phase. These results suggest that although Kelvin waves are known to be a global scale phenomenon, their influence on convection is significantly connected to local scale factors, particularly during an extreme WNP monsoon phase over the region of Indonesia. A lack of relationship shown by ER and MRG waves with local factors during both extreme WNP and AU monsoon phases (except for the MRG wave in Makassar during an extreme WNP monsoon phase), suggest that these waves are insufficient in intensifying convection in the region of Indonesia, related to Asian-Australian monsoon. Further study with more complex datasets with greater spatial coverage is required to ascertain more detail on local-CCEW relationships, particularly over the eastern part of the Indonesian region.

ACKNOWLEDGEMENT

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Social network analysis of local water user associations' actors: evidence from Iran

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ABSTRACT. The purpose of this study was to investigate social network analysis (SNA) indicators of actors among exploiters, members of local water user associations (WUA), and their boards of directors in Ilam Province, Iran. The network analysis method and Ucinet6 software were used to examine the information exchange network and the network of participation among the members of the WUAs across the province. The actors of the local WUAs in the study area included the Water Supply Organization, the Agri-Bank, the Agricultural and Natural Resources Management Organization, the Agriculture Organization, the Department of Cooperatives, Labor and Social Welfare, the Provincial Government, the Village Council and Rural Municipalities, the Agricultural Insurance Fund, and the Regional Water Company of the province. Among the experts, one was selected from each organization or administration via the purposeful sampling method. A questionnaire containing 20 items with a Likert-type scale was designed for data collection, and the actors active in the field of local WUAs were asked to determine the information exchange rate and the participation of their organization/administration with other organizations/administrations. In addition, the relationship between the active actors and local WUAs was examined from the perspective of the actors in the province. The results of the analysis of the density index at the whole level of the information exchange network and the participation network showed that the density of the links to exchange information and participate in the network of actors was low across the provincial WUAs. In total, according to network density indicators, network size, centrality (concentration) of the entire network, and the social cohesion of the information exchange network and the network of participation were ranked to be weak to moderate.

KEYWORDS: Social network analysis, actors, WUAs, Ilam Province.

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1. INTRODUCTION

Water is an important factor in agriculture and plays a decisive role in economic growth and development. Water scarcity is a growing concern in most developing countries, calling for more advanced patterns of water consumption and sound irrigation policies (Hadizadeh et al. 2018; Valizadeh et al. 2019). According to the National Drought and Crisis Management Agency of Iran's Meteorological Organization (2016), Iran has been suffering from mild drought for the last 5 years, and the last wet year of the country occurred at around 2006-2007. Considering that about 70 percent of the global water resources are consumed by agricultural activities, the actors of this economic sector must develop and adopt mechanisms for balanced and optimal water consumption (Aminian 2009). Thus, given the water resource crisis and the management crisis that have been plaguing many of the provinces and watersheds of the country in recent years, participatory management and stakeholder participation in planning and decision making can facilitate and accelerate the achievement of sustainability in water resource management while increasing confidence in success.

Ilam province is currently suffering from a lack of water resources (Regional Water Company of Ilam Province 2016). In addition to severe water scarcity, the enforcement of a subsidy reform, the increase in water and energy costs, and the imminent implementation of fair water distribution, which will not be efficient under the status quo of agricultural water use in the region, will increase production costs and decrease income, thereby further complicating the agricultural problems of the region. A reasonable solution for these problems is the adoption of participatory management of agricultural water use and the improvement of irrigation efficiency (Nejadrezaei et al. 2018). However, to implement water resources management, it is necessary to consider important social components and influential indicators. Social capital is one of the important factors in the relationship among stakeholders, which is investigated on the basis of network analysis methodology prior to the implementation of participatory water resources management and any water-related projects based on the participation of local communities, leading to a deeper understanding of the challenges and opportunities faced by managers and planners. In general, social capital has a positive effect on the interaction of participants in a social network (Kim, Hastak 2018).

Social network analysis (SNA) focuses on the structure of ties within a set of social actors, e.g., persons, groups, organizations, and nations, or the products of human activity or cognition such as web sites, semantic concepts, and so on (Carrington et al. 2005; Tulin et al. 2018). It was developed in the 1930s to investigate the link between local patterns of human relationships and social processes, such as the impact of social groups on the likelihood of being obese (Farine, Whitehead 2015). The aim of social network analysis is to understand a community by mapping the relationships that connect its members as a network and then trying to draw out key individuals, groups within the network ('components'), and/or associations between individuals (Bodin, Crona 2009). This approach will generate diagrams that will show the relationships between individuals, contained in data.

Since the late 1980s, the tendency to transfer water resource management and irrigation networks from the public sector to water user associations (WUAs) has been enhancing increasingly with the use of exploiter participation, as this is the case in many water-scarce countries as the national determination and politics (Sajasi et al. 2014). In fact, companies such as local WUAs have been established to operate and maintain water management networks, with the main objective of optimizing water resources management for sustainable development (Mirzai et al. 2011). These companies use human, physical and natural capital in the framework of participatory management for sustainable development. Therefore, WUAs represent the first form of a participatory management approach adopted by the water management sector (Hassabou, El-Gafy 2007).

Various studies have examined WUAs in Iran and other countries, approaching the subject matter from different dimensions. For example, a study conducted by Sabouri et al. (2014) showed that member farmers had higher participation in social activities than non-member farmers, along with a larger network of social relationships, higher social trust, and strong social cohesion, benefitting from further activities and promotional programs. In this regard, Salari et al. (2015) assessed the social capital of the local stakeholder network of water in the customary system of Resin Village with respect to local water management. Their results emphasize the use of the SNA method in local water management, and the authors noted that the use of this method and the measurement of social capital would contribute to improving participatory water management to maintain and develop water resources. This is mainly because poor social capital and the lack of unity among individuals would impair trust and participation, and consequently, good governance would challenge water resources. Ebrahimi et al. (2014) analyzed a social network of stakeholders in the Water Management Action Plan for Water Resources in Jajroud River and concluded that strengthening social cohesion and social capital among local stakeholders was a requirement for the Water Resources Participatory Water Management Action Plan to achieve water sustainability and security. Other researchers, e.g., Facon (2002) and Kadirbeyoglu and Ozertan (2011), mentioned the lack of social capital as a reason for the failure of irrigation management transfer. In this regard, Ababneh and Al Adwan (2012) and GTZ (2010) report that the lack of a legal framework for the transfer of irrigation management, infrastructure erosion, social factors, and negative experiences with previously implemented participatory projects will result in the failure of irrigation management transfer to farmers. The results of a study by Lienert et al. (2013) on the existing policies for water infrastructure in Switzerland, using SNA, showed that this approach could provide appropriate and good results that could be used to address various problems in stakeholder relationships, affecting decision-making and water policy issues. Similarly, Stein et al. (2011) analyzed the role of social networks and the impact of these networks on good water management practices in a water basin in Tanzania. The result emphasized the application of network analysis as a systematic way of describing the relations between local stakeholders for water governance and considered the presence of local leaders in the villages as one of the main components of this process.

Fliervoet et al. (2016) conducted a social network analysis of floodplain management in the Dutch Rhine Delta and showed the dependence of non-governmental actors on the main governmental organizations. It seems that the Dutch governmental organizations still play a dominant and controlling role in floodplain management, challenging the alleged shift from a dominant government towards collaborative governance and calling for a detailed analysis of actual governance. Chaffin et al. (2016) presented a method for resolving this problem by describing the results of an institutional SNA aimed at characterizing the changing governance network in the Klamath River Basin, USA, during a period of contested nego-

Table 1. Actors of Local Water User Associations in Ilam Province

Actors	Interviewee	Duration of the interview (min)	Abbreviation of actors
Water Supply Organization	Co-operative Managing Director	60	ACO
Agri-Bank	Deputy Chief and Supervisor	35	AB
Agricultural and Natural Resources Management Organization	Head of the organization	35	ANO
Agriculture Organization	Technical deputy	45	AO
Department of Cooperatives, Labor and Social Welfare	Deputy Director-General of Cooperatives	40	COA
Provincial Government	Deputy of planning	30	GO
Village Council and Rural Municipalities	Presidency of the Council	55	IC
Agricultural Insurance Fund	Agricultural insurance expert	35	IFA
Regional Water Company	Expert on Ilam Regional Water Distribution	30	WO

Table 2. Important indicators in social network analysis (source: Bodin, Crona 2009; Ghorbani et al. 2013; Rezaei et al. 2015)

Indicators	Description
Density	The ratio of all available ties to all possible ties. Therefore, the density is referred to as the number of ties associated with a node and, in other words, nodes that are related to the considered node.
Centrality	The strength of a node based on the amount of relation on the network. Centrality can be discussed regarding the location of the node, the type of tie, and the relation.
In-degree centrality	The number of nodes that an actor receives. A high in-degree reflects a person's reputation or authority.
Out-degree centrality	The number of nodes leaving an actor. The high out-degree indicates the influence of the actor, which is further discussed in the data transmission network.
Reciprocity	This indicator plays a role in determining the sustainability of the network and is obtained by examining the interaction between actors.
Transitivity	This indicator comes from sharing ties between three individuals, one of which is the bridge between the two other people. As the number of people transporting ties is higher, this rate is higher, and as a result, relationships sustain among actors.
Network size	The number of ties in a network of relations. As the number of ties increases, the density will increase in the network of relations.

tiations over water. The results showed that employing this type of SNA is useful for describing potential and actual transitions in governance that yield increases in adaptive capacity to respond to social and biophysical surprises such as increasing water scarcity and changes in water distribution.

Ogada et al. (2017) used stakeholder analysis and social network analysis to analyze stakeholders' social and structural characteristics based on their interests, influence, and interactions regarding the Lake Naivasha basin, Kenya. Interactions in the basin are guided by stakeholders' interest and sphere of influence, which have both promoted participation in implementing a collaborative water governance framework.

According to a previous study, the establishment of local WUAs has accelerated the development of water distribution networks, and exploiters have been encouraged to participate financially and to exploit water management systems (Heydarian 2003). On the other hand, researchers have considered the increased social cohesion, development of social participation, and, most importantly, the mutual trust of individuals as the necessary conditions for the development of any society (e.g., Bhagavatula et al. 2010). Trust is the main factor of development and one of the most important components of social capital. There is a significant relationship between the level of trust and the development of societies, and therefore, developed societies have higher levels of trust than other societies (Fukuyama 2001). In fact, trust is a precondition for participation and cooperation, and the survival and sustainability of the relations between actors depend on the trust of individuals. Also, trust can play an important role in resolving disputes and conflicts among exploiters in the process of water resource management (Bodin, Prell 2011). The results of various studies show that the use of social network analysis is effective in local water governance and measuring social capital can improve participatory water management in order to conserve and develop water resources. Because the weakness of social capital and the lack of unity and unity among individuals will lead to a loss of trust and participation, this will challenge the adequate governance of water resources. Therefore, the purpose of the present study was to investigate the indicators of social network analysis of actors among exploiters, members of local WUAs, and their boards of directors in Ilam Province.

2. METHODOLOGY

2.1. STUDY AREA

Ilam Province, one of the 31 provinces of Iran, is located in the western part of the country, bordering Iraq. In 2014, it was placed in Region 4. Covering an area of 19,086 square kilometers (about 4.1% of Iran), Ilam Province shares its borders with three neighboring Iranian provinces and Iraq: Khuzestan Province in the south, Lurestan Province in the east, Kermanshah Province in the north, and Iraq in the west, with 425 kilometers of common border. The population of the province is approximately 600,000 people (2015 estimate). The counties of Ilam Province are Eyvan County, Chardavol County, Sirvan County, Ilam County, Malekshahi County, Mehran County, Badreh County, Darreh Shahr County, Abdanan County, and Dehloran County. The northern region of Ilam, due to its high elevation, experiences cold winters and mild summers and receives the highest amount of precipitation in the province. The variety of land is one of the main reasons for the prevalence of nomads in the area (Aliakbari et al. 2015).

2.2. SAMPLES AND DATA COLLECTION

A survey study was designed for data collection. The statistical population of the study was composed of the actors of the local Ilam WUAs, including the Water Supply Organization, the Agri-Bank, the Agricultural and Natural Resources Management Organization, the Agriculture Organization, the Department of Cooperatives, Labor and Social Welfare, the Provincial Government, the Village Council and Rural Municipalities, the Agricultural Insurance Fund, and the Regional Water Company of the province. During data collection in 2018, one person from each organization or administration was selected as a contact person (Table 1).

2.3. DATA ANALYSIS

We used a quantitative research approach in terms of paradigm; the survey was applied and descriptive. The network analysis method and the Ucinet6 software were used to examine the information exchange net-

Table 3. Review of the information exchange network and the participation network in the current situation among actors from their point of view

Actors	View of the actors	Items			
		No relation	Low	High	Very high
Regional Water Company	Views of actors about the information exchange network (people)	29	83	253	0
	Views of actors about the participation network (people)	20	229	116	0
Agricultural Insurance Fund	Views of actors about the information exchange network (people)	48	330	14	0
	Views of actors about the participation network (people)	45	302	18	0
Water Supply Cooperative	Views of actors about the information exchange network (people)	19	45	301	0
	Views of actors about the participation network (people)	3	114	248	0
Agri-Bank	Views of actors about the information exchange network (people)	20	327	18	0
	Views of actors about the participation network (people)	52	289	24	0
Agricultural and Natural Resources Engineering Organization	Views of actors about the information exchange network (people)	200	155	10	0
	Views of actors about the participation network (people)	207	156	2	0
Village Council and Rural Municipalities	Views of actors about the information exchange network (people)	30	324	11	0
	Views of actors about the participation network (people)	268	66	31	0
Department of Cooperatives, Labor and Social Welfare	Views of actors about the information exchange network (people)	92	263	10	0
	Views of actors about the participation network (people)	92	263	10	0
Agriculture Organization	Views of actors about the information exchange network (people)	83	194	88	0
	Views of actors about the participation network (people)	183	120	62	0
Provincial Government	Views of actors about the information exchange network (people)	344	20	1	0
	Views of actors about the participation network (people)	344	20	1	0

Table 4. Indicators of network analysis of actors of local water user associations

Link type	Number of organizations	Total expected links	Network size (number of available relations)	Density [%]	Reciprocity [%]	Transitivity [%]	Centrality of total network based on internal links (input)	Centrality of total network based on external links (output)	Total centrality
Information exchange	9	420	299	36.7	55.5	32.35	15.65	26.73	36.7
Participation	9	420	296	36.5	55.5	32.47	13.16	29.78	36.5

work and the network of participation among the members of WUAs across the province. This software is one of the most widely used social network analysis software packages to draw up social networks and create and display multiple relations in these networks. It uses a set of nodes representing the variables of the research and a series of ties between nodes to show the relations and drawings within the social network. The social network can quantitate the qualitative data using mathematics, and thus, the differences are generally represented in the form of a series of indicators, enabling comparisons and analysis (Alizadeh, Siddiqi 2013). In the study of the existing status of actors in the local Ilam WUAs, a questionnaire composed of 20 items with a Likert-type scale (no relationship to very strong relationship) was designed, and the active actors in the field of provincial WUAs (Table 1) were asked to express the amount of information exchange and the participation rate of their organization/administration with other organizations/administrations during 1 year. In addition, the relationship between active actors with respect to the local WUA in the province was examined from the perspective of actors.

There are many indicators to analyze social networks. One of the main indicators is centrality, according to which the in-degree centrality is the degree of reputation and authority of each actor and the out-degree centrality indicates the social or political influence of the actor. Also, indicators such as density, reciprocity, transitivity, and network size are among the indicators used in this study (Table 2). The values for each index are calculated from 100; values below 50 indicate a weak index, and values above 50 indicate a strong index.

3. RESULTS

3.1. INFORMATION EXCHANGE NETWORK AND PARTICIPATION NETWORK AMONG ACTORS OF LOCAL WUAS

To examine the information exchange network and the actor participation network, actors were asked to determine the extent of their work relationship with other actors in the province on a Likert scale. The actors of the local WUAs in the province of Ilam include the Water Supply Organization, the Agri-Bank, the Agricultural and Natural Resources Management Organization, the Agriculture Organization, the Department of Cooperatives, Labor and Social Welfare, the Provincial Government, the Village Council and Rural municipalities, the Agricultural Insurance Fund, and the Regional Water Company of the province. One expert was selected from each organization or administration. In total, according to Table 3, Water Supply Cooperatives and Regional Water Companies of the province were the main and most important actors from the perspective of local WUAs, and the Agricultural and Natural Resources Engineering Organization and the Provincial Government were the two actors that most organizations were unrelated to.

3.2. RELATIONSHIP OF ACTORS ON THE ACTIVITIES OF LOCAL WUAS WITHIN INFORMATION EXCHANGE NETWORKS AND PARTICIPATION NETWORKS

The structural analysis of the social network of actors of local WUAs at the provincial level was studied in the form of an information exchange network and a participation network. The indicators examined for SNA are presented in Table 4.

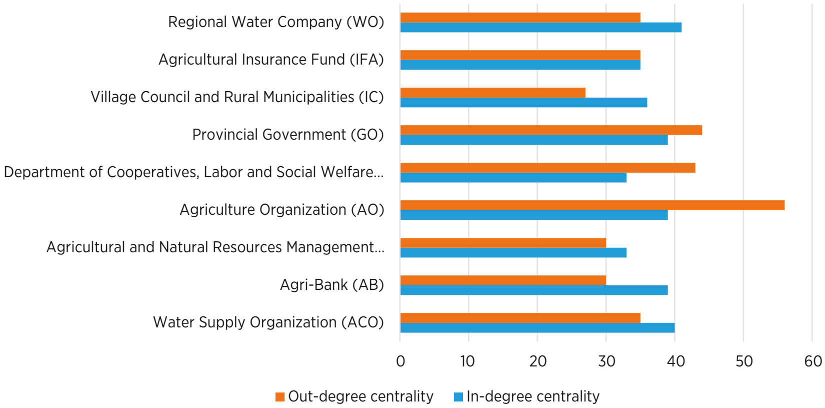

Fig. 1. In- and out-degree centrality in the information exchange network of actors of the local WUAs

3.3. INFORMATION EXCHANGE NETWORK FROM THE PERSPECTIVE OF LOCAL WUA ACTORS

The result of the analysis of the density index at the total level of the information exchange network shows that the size of this index was 36.7 percent at the total level of information exchange links (Table 4). This value indicates the low density of information exchange links in the network of actors in the local WUAs in the province. Since the density is directly related to social cohesion, the level of social cohesion was also weak.

According to the results, the size of the network shows 299 connections from all expected links (420 cases), that is, more than half of the expected links have been formed. As the size of the network increases, the density of the network also increases. Thus, based on the size of the network, the density and social cohesion are at a moderate level. Another indicator focused on to study social cohesion is the centrality (centration) of the entire network based on internal and external links. According to the results (Table 4), the focus of the network has increased more on the basis of external links than on the internal links in the information exchange network. This means that it was not affiliated with central actors based on internal links or network information reception; receiving information is not in their monopoly, and more people are effective in information reception. However, according to external links, the dispersion of information is monopolized by limited and fewer individuals. In total, according to the indicators of the network density, network size, centrality (concentration) of the entire network, and the social cohesion of the information exchange network are weak to moderate.

Given that the reciprocity index of links expresses the mutuality of the relationships in the network, it can be stated that network sustainability has a direct relationship with the reciprocity rate of links. According to the results, the reciprocity of links in the information exchange network of actors of local WUAs was 55.5 percent. Therefore, based on this indicator, it can be said that the sustainability of the information exchange network is moderate. In addition to the reciprocity index, the index of transitivity of the links also indicates the sustainability of the network in that the value of this index was 32.35 percent according to the results of the study, indicating that sustainability is weak in the information exchange network. In general, according to the two indicators of reciprocity and transitivity of links, network sustainability is weak to moderate. To investigate the role of different organizations in the information exchange network, the values of the in- and out-degree centrality were compared (Fig. 1).

The in-degree centrality is the number of nodes that an actor receives. A high in-degree reflects the reputation or authority of an actor. According to Figure 1, the Regional Water Company, with the highest in-degree centrality (41), followed by the Water Supply Cooperatives, with an in-degree centrality of (40), had the highest authority and reputation and are therefore the most trusted actors in the information exchange network of local WUAs of the province. However, the actors believed that the Department of Cooperatives, Labor and Social Welfare, and the Provincial Government had the lowest position among actors in terms of information in-degree, and this finding does not seem desirable.

A high out-degree centrality also reflects the influence of an actor. Thus, as evident in Figure 1, the Agriculture Organization of the province is considered the main actor in social influence and has the most public relationships with other actors in the field of information exchange. The Provincial Government and the Department of Cooperatives, Labor and Social Welfare are at the next ranks of social influence. The Islamic Council and Rural Municipalities are ranked the last in social influence in terms of information exchange. Although Water Supply Companies and the Regional Water Company have good centrality in information exchange and are highly trusted and authority actors, they are in a lower position in terms of out-degree centrality and social influence (out-degree centrality of 35).

3.4. PARTICIPATION NETWORK FROM THE PERSPECTIVE OF LOCAL WUA ACTORS

The low density value of 36.5 percent in the links of the participation network of actors of local WUAs represents social cohesion and, consequently, poor social capital in the participation network of actors of local WUAs. According to the results of the study, the participation network size is 296 links of the 420 expected links, suggesting that more than half of the expected links have been formed in the participation network. Based on the network size index, the density and subsequent social cohesion of the network are moderate. To investigate social cohesion, the index of total centrality (total concentration) was also examined; based on the results (Table 4), the concentration of the network has increased on the basis of external links to the internal links in the participation network. This means that according to the internal links of the network, it has not been dependent on the central actors and their activity monopoly, and more people are effective in receiving participation. However, based on external links, the dispersion of participation and participatory activities occurs by fewer individuals. In comparison with the information exchange network, dispersion of participation is made in the form of a more compact structure because the centrality of the participation network is more based on the external links than the information exchange network. In general, according to the network density indicators, network size and total network centrality (concentration), actor participation network, social cohesion, and social capital are weak to moderate.

Based on the results presented in Table 4, the reciprocity of the links in the participation network (interactions) of the local WUAs was 55.5 percent, indicating the sustainability of the participation network. Also, the value of the transitivity index of 32.47 percent represents the poor sustainability of the participation network of local WUA actors. Therefore, considering the reciprocity and the transitivity of the links, network sustainability is weak to moderate.

To examine the role of various organizations in the participation network of local WUAs, the in- and out-degree centralities were calculated (Fig. 2).

According to Figure 2, the Agriculture Organization of Ilam Province had the highest in-degree centrality (46), followed by the Regional Water Company (41) and the Water Supply Cooperative (40) with the highest reputation and power among the actors of the local WUAs, considered the most trusted actors in the field of participation. This indicates the awareness of other actors about the role of these two sets in the field of local WUAs in the province. However, according to the actors, the Islamic Council and the Agricultural Engineering Organization have the lowest position in participation in terms of authority and reputation, and there is a need to strengthen their position. The high out-degree of centrality represents the actor's influence. According to Figure 2, the Department of Cooperatives, Labor and Social Welfare, he Agriculture Organization, the Provincial Government, the Regional Water Company, and the Water Supply Cooperative with the highest out-degree centrality values (47, 44, 42, and 35) are the most influential actors, while the Insurance Fund has the lowest level in terms of social participation in the partnership network. According to Figure 2, the Islamic Council and the Rural Municipalities not only have a weak position in terms of authority and reputation, but they also require further attention and improvement in relation to social influence (their in- and out-degree centralities were 30 and 29, respectively).

The QAP indicator is used in the Ucinet software to examine the correlation between the links of the information exchange network and the partnership network. Based on this indicator, the correlation between two networks of information exchange and participation has a high coefficient value (correlation coefficient = 0.95), and the significance level of the correlation between these two networks is zero. This value expresses the significance of the correlation between the two links of information exchange and participation at the significance level of 1 percent.

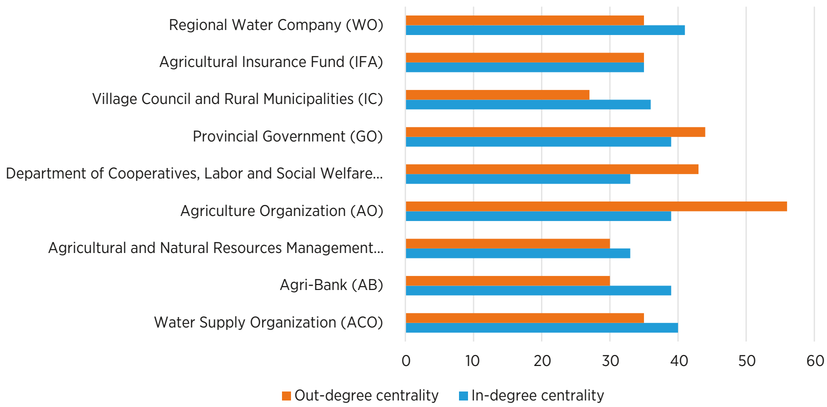

Fig. 2. In- and out-degree centrality in the participation network of local WUAs

Accordingly, if there is a link between the two actors of the local WUAs, there is a participation link between the two actors of the local WUAs with the probability of 1 percent. Thus, the information exchange network serves as a starting point and the foundation or facilitating factor for the participation network.

4. DISCUSSION AND CONCLUSION

As previously stated, social network analysis is a new approach to planning for participatory water resources management. By studying social networks using network analysis techniques, researchers can identify challenges to participatory processes in the management of water resources (Bodin, Crona 2009). The results of this study show that Water Supply Companies and the Regional Water Company of the province are the main and most important actors from the viewpoint of the actors of local WUAs, while the Agricultural and Natural Resources Engineering Organization and the Provincial Government are two actors that most organizations are unrelated to. Therefore, the strengthening of relationships with these organizations is necessary, and measures should be taken to facilitate the relationship with these organizations, such as the reduction of the administrative bureaucracy process.

The results of the analysis of the density index at the whole level of the information exchange network show that the density in the links of information exchange in the network of actors of local WUAs in the province is low. Taken together, according to the network density indicators, the network size, the centrality (concentration) of the entire network, and the social cohesion of the information exchange network are at a weak to moderate level. These results are consistent with the results obtained by Taghipour et al. (2015) and Sabouri et al. (2014). Therefore, participatory management in local WUAs is challenging, and efforts to increase the density of these associations are essential.

Based on the results, the Regional Water Company, with the highest in-degree centrality, and the Water Supply Cooperative have the first and second highest authority and reputation, respectively, and are the most trusted actors in the information exchange network of local WUAs in the province. However, according to the views of the actors, the Department of Cooperatives, Labor and Social Welfare and the Provincial Government have the lowest position among the actors in terms of information input degree, and this finding does not seem desirable. According to the results, the Agriculture Organization, the Regional Water Company, and local WUAs are the most trusted actors and enjoy greater influence. Therefore, these organizations can be used to encourage exploiters and actors to participate with each other and to strengthen the role of other organizations in the network of relations between actors.

The transitivity rate of the links also reflects the poor sustainability of the participation network of local WUAs; therefore, considering the reciprocity and transitivity of the links, network sustainability is weak to moderate. The Agriculture Organization in the province of Ilam, with the highest in-degree centrality, and the Regional Water Company and Water Supply Cooperative have the highest reputation and authority among the actors of the provincial WUAs and are therefore considered the most trusted actors in the field of participation. This indicates the high awareness and familiarity of other actors with the role of the two sets in the field of local WUAs in the province. According to the actors, the Islamic Council and the Agricultural Engineering Organization have the lowest position in participation in terms of authority and reputation and are therefore advised to improve their position. In addition, the Department of Cooperatives, Labor and Social Welfare, the Agriculture Organization, the Provincial Government, the Regional Water Company, and the Water Supply Cooperative exhibit the highest out-degree centrality and are the most influential actors. However, the Insurance Fund showed the lowest level in terms of social participation in the partnership network. According to the results, the Islamic Council and the Rural Municipalities not only have no good position in terms of authority and reputation, but they also need to improve their position with respect to social influence. Based on the results, to improve the social cohesion and participation of the exploiters of the local WUAs, several training courses are proposed to familiarize people with WUAs and their limitations. Quantity orientation is also prohibited in the establishment of cooperatives, and few WUAs should be established, but consciously and with awareness of the people. It is suggested to create and strengthen social capital in the villages by associations through the expression of the importance of collective actions in the form of associations and co-operatives and the common interests of these activities through radio, television programs, and visiting successful associations.

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Environmental modeling in small catchments in the context of climate change: Reda case study

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ABSTRACT. The BONUS MIRACLE project focuses on understanding the of the impact of climate change on water environments, including it's affects on hydrological regimes and nutrient concentrations. The overall objective of MIRACLE is to initiate a social learning process in collaboration with stakeholders, that can identify new configurations for governance (conceptual, institutional, and practice based) in order to reduce nutrient enrichment and flood risk in the Baltic Sea region. These configurations should be understood as new solutions to protect water resources, ecosystem services and provide win-win solutions. To achieve this environmental modelling of the Reda catchment, Poland, is used as a pilot study for the project. Mathematical models which specified the detailed processes associated with water cycles, including determining interconnections and quantifying variables characteristic to the assessment of the water resource quantity and quality, were found to be useful. Due to the complexity of some models, launching, entering the appropriate data in the correct formats and calibrating the models proved to be challenging. Future developments in the water management sector should concentrate on specific local catchment areas where the application of integrated water resource management principles and the adaptation to climate change are more easily merged with local spatial planning. However, a larger number and higher frequency of measurements would be required.

KEYWORDS: Eutrophication, modeling climate change, nutrient mitigation.

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1. INTRODUCTION

As a consequence of increased anthropogenic greenhouse gas emissions, it is hypothesised that the Earth's climate will be warmer in the future (IPCC 2018). This change will mainly affect future generations and the scale of warming will depend on the path of development world chooses. Climate change will affect environmental resources, for example changes in the amount and distribution of precipitation, which will alter the human demands for their ecosystem services, as predicted by climate models.

The European Union has developed a common approach to environmental issues based on the principle of sustainable development, which proposes prudent and economical use of environmental resources to prevent excessive use and degradation which does not lead to a deterioration of the quality of life and limit the development potential of future generations[1]. The current outlook on climate change, as well as the need to take into account a long term perspective, does not change the general objectives of managing environmental resources. Water provides a key ecosystem service, hence the principles of its management are particularly important. This problem is acknowledged globally, resulting in the collaboration of an international community of specialists and politicians through the Integrated Water Resources Management (IWRM) framework. According to Global Water Partnership GWP[2], the IRWM "is a process that promotes coordinated management and development of water resources, land and related resources in order to maximize economic and social impact without compromising the balance of key ecosystems" (Hassing et al. 2009).

Climate change has a significant impact on the management of energy and water resources. It can cause violent meteorological and hydrological phenomena as well as changes in the hydrological regime. In the BONUS MIRACLE[3] (Mediating IntegRated ACtions for sustainable ecosystem services in a changing CLimatE) project, analysis of these issues for the small catchment area of the Baltic Sea Region (BSR) was undertaken. The overall objective of MIRACLE was to enact a social learning process that will lead to the identification of new configurations for governance (conceptual, institutional, and practice-based) to reduce nutrient enrichment and flood risk in BSR. One of the pilot catchments for the project was the Reda catchment, Poland. The Reda river catchment was chosen as a pilot study area because it is the largest river that drains water into the Bay of Puck where it has a significant impact on the water quality. The waters and sediments of the Bay of Puck are characterized by an excessive amount of nutrients. The Pomeranian voivodeship spatial development plan (PZPWP 2009) stated that the most important factor degrading coastal waters is excessive discharge of nitrogen and phosphorus compounds and organic substances, which enter Bay of Puck directly from the land or through river runoff, which is increased by limited water exchange with the Baltic Sea.

2. THE STUDY AREA
2.1. MORPHOLOGY

The Reda basin is located in four mesoregions (Kondracki 2011). The northern part is located in the Choczewo Heights and the Reda-Łeba proglacial valley, while the central and southern parts are situated in the Kashubian Lakeland and the eastern part, where the mouth of the river Reda is located, lies in the Kashubian Coastland mesoregion (Fig. 1).

The basin morphology, elevation and distance from the sea are varied thus local climate is diverse. The highest area is located on the south with a maximum elevation 239.5 m a.s.l., while the lowest area with elevation about 50 m.a.s.l.s located in the Reda-Łeba floodplain (Fig. 2), where the mouth of the Reda is located.

The Reda river flows roughly from the south to the north in the upper basin, before changing course downstream of Zamostne village to run from west to east. The latitudinal extent of the basin is 0°28′ (about 33 km), with the western parts of the basin located furthest from the sea.

According to Woś typology (Woś 1993) which refers to the frequency of weather types, the Reda River basin lies in two climatic regions: Lower Vistula and Eastern Pomerania. The weather in the Lower Vistula region is characterized by either cool air with high humidity and no precipitation, or frosty and very cool conditions with high cloud cover and no precipitation. Alternatively, weather in the Eastern Pomerania region is characterized by cool air temperatures, very cloudy skies and precipitation.

The Baltic Sea – mostly the Gulf of Gdańsk – impact the thermal conditions of the study.

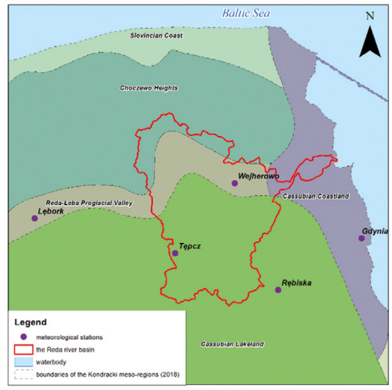

Fig. 1. The Reda basin location within the Kondracki mesoregions (Kondracki 2011)

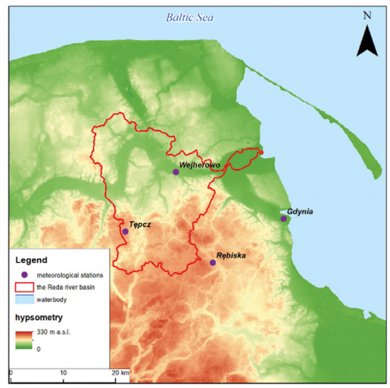

Fig. 2. Hypsometric map of the Reda basin and surroundings; max. basin elevation: 239.5 m a.s.l.

Thus, remarkable climate characteristics appear, i.e. lengthened spring and winter transition periods, small monthly and diurnal temperature amplitude, lower average temperature during spring than autumn and strong winds with increasing speed in autumn and winter (Staszek, Kistowski 1999; Miętus et al. 2004).

2.2. LAND USE, HYDROGRAPHY, HYDROLOGY AND WATER QUALITY

The catchment area of the Reda River is 485 km^2. According to the data from the Central Statistical Office, more than 206,000 inhabitants lived in the Reda River basin in 2015. The Reda catchment has an asymmetrical hydrographic network structure. The catchment of the left-bank tributaries is only approximately ¼ of the entire Reda catchment area. The largest tributary of the Reda is Słuszewska Struga which is the right-bank tributary.

[1] https://ec.europa.eu/environment/eussd/
[2] https://www.gwp.org/en/GWP-CEE/about/why/what-is-iwrm/
[3] BONUS MIRACLE has received funding from BONUS (Art 185), funded jointly by the EU and the national funding institutions Innovation Fund Denmark, Forschungszentrum Jülich Beteiligungsgesellschaft mbH (FZJ-Bt.GmbH), Latvian Ministry of Education and Science, National Centre for Research and Development in Poland, and the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS).

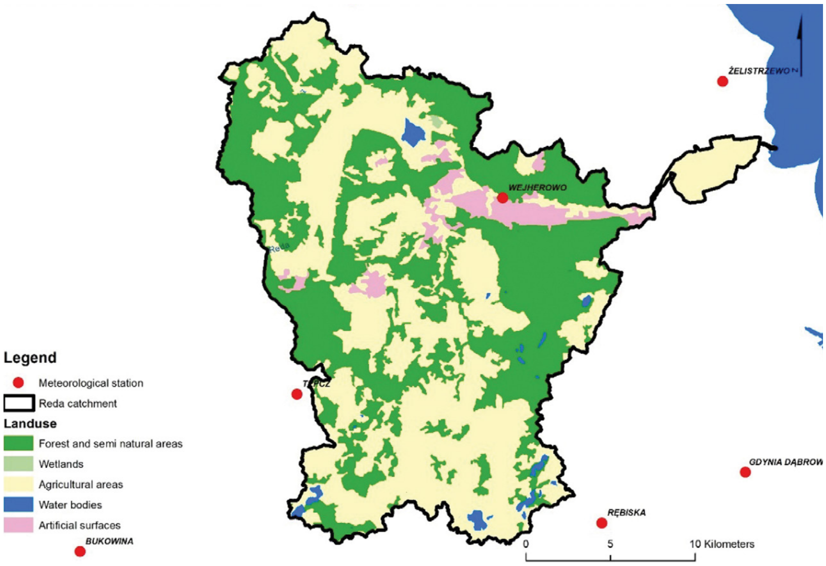

Fig. 3. Land cover in the catchment area of Reda River (based on Corine Land Cover 2006[4])

Table 1. Weather stations characteristics included in the analysis

No.	Weather station code	Station	Initial measurement	Altitude (m a.s.l).	Longitude	Latitude
1	125	Lębork	1966	38	17°43'	54°33'
2	1402	Gdynia	1951	2	18°34'	54°31'
3	91429	Wejherowo	1951	40	18°14'	54°36'
4	91426	Tępcz	1958	170	18°03'	54°30'
5	91425	Rębiska	1960	17	18°20'	54°27'

Urbanized parts of the catchment are localized in the downstream part of the river. Agricultural areas are localized close to the Reda River and its tributaries as they are dependent on irrigation (Czarnecka 2005). The land use is dominated by agriculture (arable land, heterogeneous agricultural areas and pastures) and forest, covering 51% and 44%, respectively. Agricultural areas dominate in both the upper areas of the catchment and around the estuary. Approximately 4% of the catchment is covered by artificial surfaces, while wetlands and water bodies cover an insignificant area of the catchment (Fig. 3).

One of the most significant risks in the Reda catchment is flooding caused by heavy rains, snowmelt and local water jams In the coastal zone of the Gulf of Puck, flood risk is increased by storm surges caused by strong winds. An additional problem is the accumulation or retention of water in urbanized areas following heavy rains, particularly in the cities of Reda and Wejherowo. Coastal areas at risk of storm surges, as well as lower parts of the Reda River are protected by the levees. On the other hand, the most urbanized Reda River section from Wejherowo to Reda City is not embanked. Suburbanization and chaotic development of the inhabited areas including intensive development of housing (e.g. Moście Błota in the Kosakowo commune) alongside existing settlements, further raise the flood risk.

The main flow characteristics of the Reda River at the cross section in Wejherowo are following:

- maximum observed flow (WWQ) – 20.9 $m^3 s^{-1}$;
- maximum average annual flow (WSQ) – 13.8 $m^3 s^{-1}$;
- average of mean annual flow (SSQ) – 4.35 $m^3 s^{-1}$;
- average of annual minimum flows (SNQ) – 1.67 $m^3 s^{-1}$;
- minimum observed flow (NNQ) – 0.67 $m^3 s^{-1}$.

There are two key point sources for nutrients loading in the Reda catchments: municipal sewage treatment plants and fish ponds.

Data for discharge and nutrient concentrations were obtained from 26 different point sources. Analysis of this data showed that the majority of municipal wastewater generated in the Reda catchment is discharged outside the catchment to the sewage treatment plant "Dębogórze" near the city of Rumia (located within the Kosakowo municipality). This sewage diversion includes parts of Reda, Wejherowo and Szemud, which are connected to the sewer system. Information on rural sewage discharges in the Reda catchment were estimated based on data on the population density outside the main urban areas.

Consumption of mineral fertilizers in terms of pure ingredient per 1 hectare (ha) of agricultural land in Pomeranian Voivodeship equals 74.8 kg N ha^{-1} and 18.3 kg P ha^{-1} in 2015. Compared to the consumption of mineral fertilizers in 2010, this was a decrease of ~2.7 kg N ha^{-1} and 6.6 kg P ha^{-1}, respectively. The highest consumption of mineral N and P was in the urban area of Wejherowo and Luzino commune. The highest consumption of mineral N per ha of agricultural land in the Reda catchment was in the Luzino commune (~67 kg N ha^{-1}). However, this rate is still ~13% lower than the average consumption of fertilizers in the Pomeranian Voivodeship. Similarly, consumption of phosphate fertilizers in the Reda catchment was highest in the Luzino commune, with an avergae consumption lower than in the Pomeranian Voivodeship.

There is a large variation in the total area of agricultural land within communes in the Reda catchment. The analysis shows that most farms in the Reda catchment are of small (1-5 ha) or medium (5-10 ha) size. Data from the Agency for Restructuring and Modernisation of Agriculture (ARMA 2016) suggests that the average size of farms in the Pomeranian Voivodeship was 19.02 ha in 2015.

In order to limit the loading of nutrients which affect the Baltic Sea, it is necessary for all farmers in Reda catchment to cooperate. This could be challenging considering the large number of small- and medium-size farms, however the overall consumption of mineral fertilizers in the Reda catchment is considered to be quite small. Results of water quality measurements at the station Mrzezino (north-east of Reda) for 2014 are as follows:

- ammonia nitrogen: 0.026-0.182 mg $N\text{-}NH_4$ L^{-1};
- nitrate nitrogen: 0.33-1.11 mg $N\text{-}NO_3$ L^{-1};
- nitrite nitrogen: 0.0110-0.0347 mg $N\text{-}NO_2$ L^{-1};
- phosphates: 0.112-0.265 mg PO_4 L^{1}.

2.3. CLIMATIC CHARACTERISTICS

2.3.1. METHODOLOGY

Climate analysis was based on data from five weather stations: Lębork (synoptic station), Gdynia (climate station), Wejherowo, Rębiska and Tępcz (precipitation station). Only Wejherowo and Tępcz are located within the Reda basin. The other

[4] https://land.copernicus.eu/pan-european/corine-land-cover/clc-2006

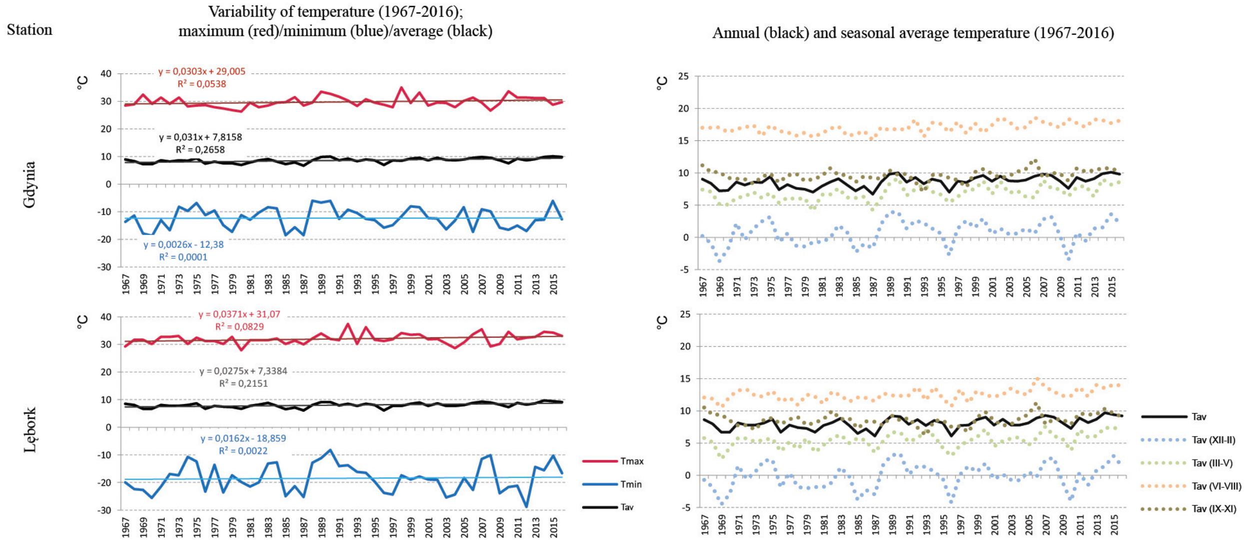

Fig. 4. Variability of annual and seasonal maximum, minimum and average temperatures at the Gdynia and Lębork weather stations, between 1967 and 2016

stations, including Gdynia (14 km east), Rębiska (2 km south east) and Lębork (17.5 km west), are at variable distances from the catchment (Fig. 2).

Five additional precipitation stations are located within 11 km of the basin. These stations were not used in the analysis as precipitation has a primarily local influence, and so interpolation could result in a misleading characterization of precipitation in the basin area (Szalińska, Otop 2012). In the authors' opinion, the spatial distribution of the weather stations analyzed in this study provides suitable coverage of precipitation data in the catchment, with suitable representation of basin landforms. Although Gdynia station is located around 14 km from the basin, it was included in the analysis as it best reflects pluvial conditions in the Reda estuary.

Variability of the temperature and precipitation over the Reda basin have been studied using the data of five stations. The analysis was conducted with verified daily data for the 50-years period from 1967 to 2016 inclusive, using temperature data from the Gdynia and Lębork weather stations and precipitation data from the Gdynia, Wejherowo, Rębiska and Tępcz weather stations.

The time period typically used to characterize a climate system is 30 years. Currently, as a result of rapid changes in the natural environment, statistical analyses of various climate elements increasingly use average values from 30 or 50 years. Therefore, taking into account the characteristic meteorological conditions, expressed by average and extreme values of meteorological elements in the catchment of the Reda River, we assessed the shorter measuring period of 2004-2014 and the longer period of 1967-2016, to emphasize the tendency of these changes.

Linear regression equations (Excel function – LINEST) were used to determine the direction and value of the tendency of changes in the considered periods. The statistical significance of this trend was defined by a significance level of $1 - \alpha = 0.95$.

2.3.2. TEMPERATURE

Annual mean temperature at the Gdynia station in period 1967-2016 varied by 3.4°C. The coldest year was 1987 with an annual average temperature of 6.7°C, while 2015 and 1990 were the hottest years with annual average temperatures of 10.1°C and 10.0°C, respectively. Annual average temperature at the Lębork station varied by 3.6°C. The coldest years were 1987 and 1996 with an average of 6.1°C, while 2014 was the hottest year with an average temperature of 9.7°C (Fig. 4).

The daily maximum temperature at Gdynia occurred on the 21 July 1988 with temperature of 35.0°C. The 95th percentile of Gdynia daily maximum temperature, based on the 50-year period 1967 to 2016 inclusive, was 25.3°C in 2010. A daily average 95th percentile value based on the period 1967-2016 was 23°C. The highest temperature of the period was 37.4°C at Lębork, occurring on 10 September 1992. The 95th percentile of Lębork daily maximum temperature based on period 1967-2016 was 28.1°C, also occuring in 2010. Its daily annual average was 26.0°C.

July and August were the hottest months, with the exception of 2000, when June was the hottest month at both Gdynia and Lębork (Fig. 5).

The daily minimum temperature at Gdynia of –18.7°C was recorded on the 2nd February 1970. The 5th percentile of Gdynia daily minimum temperature occurred in 1987 with the value of –10.4°C. A daily average value in the period was –5.0°C. At Lębork, daily minimum of –28.8°C was recorded on the 6th of February 2012. The 5th percentile of Lębork daily minimum temperature also occurred in 1987, with the value of –16.3°C. A daily average value in the period was – 5.5°C.

January and February were the coldest months at Gdynia and Lębork (Fig. 5).

Seasonal average temperatures for months December-February at Gdynia and Lębork were 0.7°C and –0.2°C, respectively; for March-May, 6.8°C and 5.5°C; June-August, 17.0°C and 12.5°C; and September-November, 9.6°C and 8.6°C. The biggest amplitude in temperature variability was recorded during winter months. In the period 1967-2016, monthly amplitude in winter reached 7.6°C at Gdynia and 7.8°C at Lębork. In spring, summer, and autumn months, the amplitude reached value 5.1°C, 3.5°C and 5.2°C at Gdynia; and 5.1°C, 4.6 °C and 5.1°C at Lębork, respectively (Fig. 5).

2.3.3. PRECIPITATION

Annual average rainfall at Wejherowo, Tępcz, Rębiska and Gdynia stations in the period 1967-2016 varied between 156.7 mm and 1,199.2 mm. The highest annual average value was recorded at 804.6 mm at the Wejherowo station. At Tępcz, Rębiska and Gdynia stations the highest annual average values were 726.5, 636.6 and 572.7 mm, respectively.

The highest annual precipitation occurred in 1980 at Wejherowo station (1,199.2 mm), 2007 at Tępcz station (1,039.2 mm), 1970

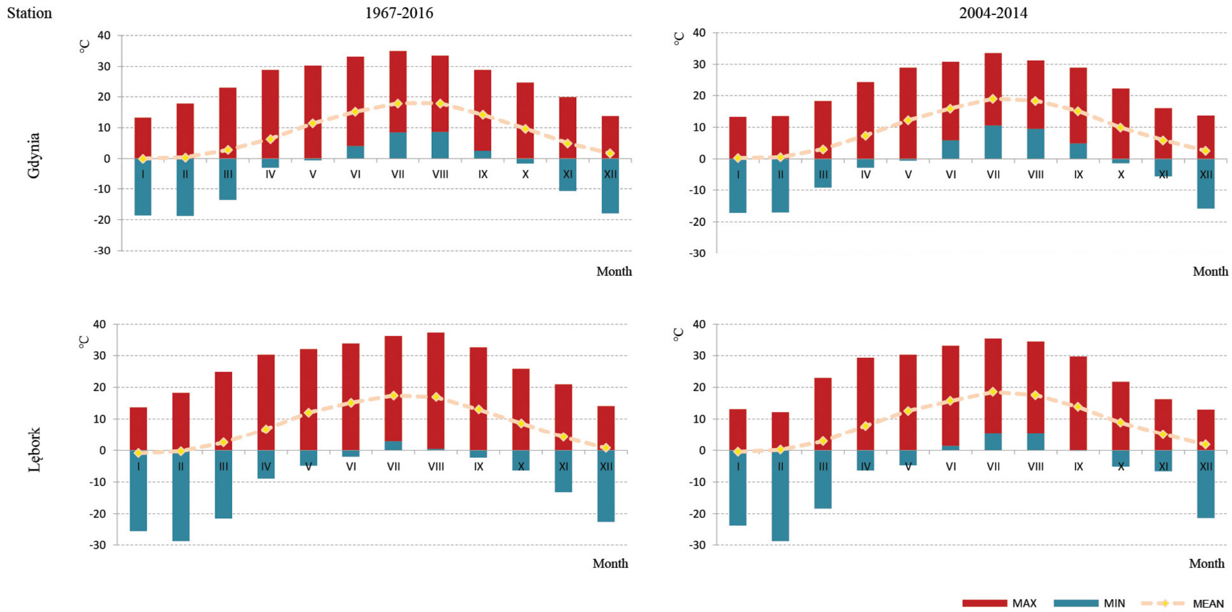

Fig. 5. Variability of monthly maximum, minimum and mean temperature (1967-2016) and (2004-2014) at Gdynia and Lębork

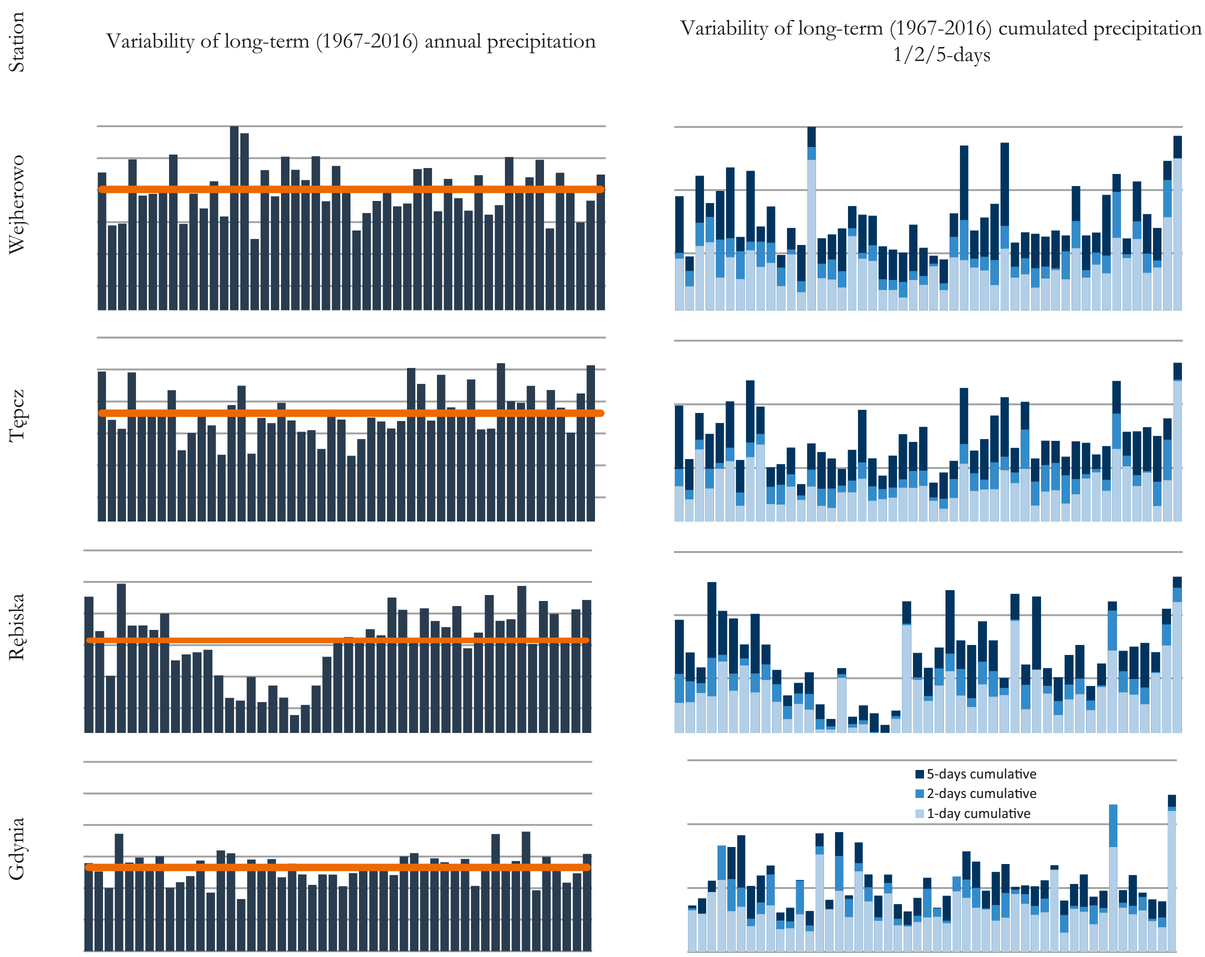

Fig. 6. Long- term variability in annual rainfall and maximum of 1/2/5-days cumulated rainfall (— trend), between 1967 and 2016

at Rębiska station (988.6 mm) and in 2010 at Gdynia station (758.2 mm). The lowest annual value was recorded at Rębiska station in 1989 (156.7 mm), Gdynia station in 1982 (330.3 mm), Tępcz station in 1992 (460.4 mm), and at Wejherowo station in 1982 (494.5 mm). Cumulative rainfall maximum for 1, 2 and 5 days were recorded as: 125 mm (2016), 134.2 (1980) and 159.1 (1980) at Wejherowo station, respectively; 118.3 mm (2016), 119.5 mm (2016) and 132.7 mm (2016) at Tępcz station; 110.4 mm (2016), 121.7 mm (2016) and 130.5 mm (2016) at Rębiska station; and 110.4 mm (2016), 115.2 mm (2010) and 123.0 mm (2016) at Gdynia station (Fig. 6).

In the period 1967-2016 the highest monthly rainfall was generally recorded in June and the lowest in April (with an exception at Gdynia station, where minimum values were recorded in February). In June the monthly average rainfall was 90.8 mm at Wejherowo, 83.8 mm at Tępcz, 77.4 mm at Rębiska and 69.5 mm at Gdynia. In April, monthly average rainfall was 42.4 mm at Wejherowo, 37.0 mm at Tępcz, and 34.6 mm at Rębiska. At Gdynia, the lowest monthly average rainfall was in February, 21.3 mm.

The monthly average rainfall was higher between 2004-2014 than between 1967-2016, with differences of 10.9 mm at Rębiska, 4.5 mm at Tępcz, 1.7 mm at Gdynia and 0.6 mm at Wejherowo.

3. MODELED IMPACTS OF CLIMATE CHANGE

Assessing the impact of future change is an essential component of modeling the impact of measures selected within the MIRACLE project. To allow for a long-term planning and management on a national level, a 30-year model period centered around 2030 (2016 to 2045) was chosen.

The changes were compared to the baseline simulation for a recent 10 year period (2004 to 2014). In the MIRACLE project, climate change impact assessments were included in the modeling for RCP8.5 projections for two regional climate model datasets: WRF-IPSL-CM5A-MR (WRF)[5] and RCA4-CanESM2 (RCA)[6] (Bartosova, Capell 2017). Two regional climate model datasets were used to show the highest increases in precipitation (WRF, RCA) and temperature (WRF, RCA) until 2030 and the effects on water and nutrient flows in the case study area. Two sub-basins related to the Reda catchment

Table 2. Comparison of monthly average temperatures in sub-basins 6351 and 6352 between model WRF/RCA predictions for scenario RCP 8.5 (2016-2045) and measurement data from Lębork/Gdynia stations (2004-2014) [°C]

Month	(2004-2014) and (2016-2045) difference							
	= WRF(6351) – Tmean(Gdy)	= WRF(6352) – Tmean(Gdy)	= WRF(6351) – Tmean(Lęb)	= WRF(6352) – Tmean(Lęb)	= RCA(6351) – Tmean(Gdy)	= RCA(6352) – Tmean(Gdy)	= RCA(6351) – Tmean(Lęb)	= RCA(6352) – Tmean(Lęb)
Jan	−0.1	−0.1	0.75	0.78	1.03	1.03	0.21	0.21
Feb	0.51	0.7	0.96	1.16	0.04	0.01	−0.4	−0.43
Mar	0.47	0.9	0.71	1.18	0.29	−0.2	0.05	−0.45
Apr	0.27	1.1	−0.27	0.54	0.21	−0.54	0.75	−0.01
May	0.43	1.3	0.17	1.06	0.24	−0.66	0.51	−0.39
Jun	−0.38	0.5	−0.12	0.75	0.3	−0.57	0.03	−0.83
Jul	−0.75	0	−0.33	0.45	1.08	0.38	0.66	−0.04
Aug	−0.1	0.6	0.81	1.52	0.26	−0.35	−0.66	−1.27
Sep	−0.49	−0.1	0.81	1.16	1.02	0.52	−0.27	−0.77
Oct	−0.62	−0.3	0.48	0.82	1.7	1.33	0.6	0.23
Nov	−2.03	−1.8	−1.28	−1.04	1.39	1.18	0.65	0.44
Dec	−1.48	−1.4	−0.68	−0.6	0.8	0.74	0	−0.06
average	−0.36	0.12	0.17	0.65	0.7	0.24	0.18	−0.28

Tmean(Gdy) – monthly average temperature [°C] in the period 2004-2014 at Gdynia; obtained from daily measurement data;
Tmean(Lęb) – monthly average temperature [°C] in the period 2004-2014 at Lębork; obtained from daily measurement data;
WRF/RCA – monthly average temperature [°C] in the period 2016-2045 from models WRF and RCA; obtained from daily scenario data

(6351 and 6352) were analyzed. The numerical designation of the sub-basins is defined by the numeration of the nearest grid of the climate model.

Climate represents only one aspect of changes we can expect to occur by the 2050s. Land use, agriculture, population, lifestyle, legislation, and economic development are also important drivers that change over time and can significantly affect generation and transport of nutrients to Baltic Sea. Thus, the possible changes modeled with HYPE (HYdrological Predictions for the Environment; see Section 4) that could occur by the 2050s can be altered by two aspects: changes in the climate forcing data and changes in socioeconomic variables.

3.1. THERMAL CONDITION

According to the WRF model, monthly average temperatures within sub-basin 6531 are predicted to decrease by –0.36°C for the period 2016-2045 (Table 2), compared to the average temperature at Gdynia for period 2004-2014. The model shows that the monthly temperature will increase by ~0.42°C in February-May, but decrease by ~ –0.74°C in July-January. Within sub-basin 6532, monthly average temperature is predicted to increase by 0.12°C (Table 2) in relation to measured values at Gdynia between 2004-2014. The monthly average temperature in July is predicted to remain unchanged. According to the model, the temperature in the basin will increase in by 0.85°C in February-June and August, whereas it will decrease in by 0.74°C in September-January, when compared to Gdynia observations.

In relation to the data from Lębork station, according to the projection, monthly average temperature will increase by 0.17°C in sub-basin 6531. Temperature increases of ~0.75°C are projected in January-March and August-October, with decreases of –0.42°C in November and December. In the model, it is assumed that the sub-basin 6532 monthly average temperature will be higher by ~0.65°C in the period 2016-2045 (Table 2). Model predictions show that January-October monthly average temperature will rise by ~0.94°C, whereas temperatures in November and December will decrease by ~ –0.82°C, when compared to empirical data from the Lębork station in period 2004-2014.

According to the RCA model, it is predicted that in sub-basin 6531 and 6532 average temperatures will increase by ~0.70°C and 0.24°C, respectively, in period 2016-2045, when compared to Gdynia empirical data. Compared to Lębork station measurements, average temperatures in sub-basin 6531 are predicted to increase by 0.18°C, but decrease in sub-basin 6532. In the RCA model, it is assumed that monthly average temperature in sub-basin 6532 in September-February and July will increase by ~0.74°C and decrease in March-June and August by ~ –0.46°C, compared to the long-term average at Gdynia.

5 https://euro-cordex.net/
6 https://www.smhi.se/polopoly_fs/1.90273!/Menu/general/extGroup/attachmentColHold/mainCol1/file/RMK_116.pdf

Table 3. Comparison of monthly precipitation in sub-basins 6351 and 6352 between model WRF/RCA predictions for scenario RCP 8.5 (2016-2045) and measurement data from Wejherowo/Tępcz stations in the period 2004-2014 [mm]

Month	(2004-2014) and (2016-2045) difference							
	= WRF(6531) – Pmean(Wej)	= WRF(6532) – Pmean(Wej)	= WRF(6531) – Pmean(Tep)	= WRF(6532) – Pmean(Tep)	= RCA(6531) – Pmean(Wej)	= RCA(6532) – Pmean(Wej)	= RCA(6531) – Pmean(Tep)	= RCA(6532) – Pmean(Tep)
Jan	11.9	−17.3	24.1	−5	15.2	−8.3	27.5	4
Feb	18.9	−3.4	30.8	8.5	25	0.1	36.9	12
Mar	21.8	−8.5	35	4.8	20.3	−7.6	33.5	5.6
Apr	10.2	7.3	12.9	10.1	14.8	11.8	17.6	14.6
May	−6.8	−24	−1.5	−18.7	8.7	−5.1	14	0.2
Jun	8.3	−2.2	13.4	2.9	11.3	−2	16.4	3.1
Jul	−24.3	−38.4	−6.7	−20.8	−13.9	−22.8	3.6	−5.3
Aug	−44.2	−53.3	−28.4	−37.5	−15.9	−20.4	−0.1	−4.6
Sep	−41.7	−43.8	−43.9	−45.9	−16.7	−27.8	−18.8	−30
Oct	8.5	−4.1	8.5	−4.1	19.4	8.9	19.3	8.9
Nov	−12.9	−21.7	−6.7	−15.5	−13.4	−21.9	−7.2	−15.7
Dec	22	−5.9	29.3	1.4	12.9	−8.4	20.2	−1.2
average	−2.4	−17.9	5.6	−10	5.6	−8.6	13.6	−0.7

Pmean(Wej) – monthly average precipitation [mm] in the period 2004-2014 at Wejherowo; obtained from daily measurement data;
Pmean(Tep) – monthly average precipitation [mm] in the period 2004-2014 at Tępcz; obtained from daily measurement data;
WRF/RCA – monthly average precipitation [mm] in the period 2016-2045, obtained from WRF, RCA models; obtained from daily scenario data

Compared with the Lębork station data, it is predicted that temperatures in December in sub-basin 6531 will remain unchanged, whereas in February, August and September temperatures will decrease by ~ –0.46°C, but increase in the other months by 0.44°C.

3.2. PLUVIAL CONDITION

WRF model projections in 2016-2045 shows that monthly average precipitation will decrease by ~ –0.1 mm and –0.5 mm in sub-basins 6531 and 6532, respectively, when compared to Wejherowo station measured data for 2004-2014. A decrease of –0.3 mm is also predicted in sub-basin 6532 compared to Tępcz station observations. In the WRF model, monthly average precipitation is assumed to increase by approximately 0.2 mm in only sub-basin 6531, compared to Tępcz measurements in 2004-2014.

In the RCA model it is predicted that monthly average precipitation will increase by ~ 5.6 mm and 13.6 mm in sub-basin 6531 compared to Wejherowo station and Tępcz station measured data for 2004-2014, respectively. In sub-basin 6532, it is predicted that monthly precipitation will decrease by –8.6 mm and –0.7 mm compared to Wejherowo and Tępcz stations, respectively.

4. DISCHARGE AND NUTRIENTS MODELING

For discharge and nutrients modeling the HYPE model (Hydrological Predictions for the Environment) was used. HYPE is an open source integrated rainfall-runoff and nutrient transfer model developed and maintained by the Swedish Meteorological and Hydrological Institute (SMHI).

To run the HYPE model for runoff and nitrogen simulation, several types of spatial data (including Digital Elevation Model, stream network, land use and soil type), time series data and statistical data were required. These datasets were gathered during the initial phase of the project and were improved during workshops. For the time series data, climate forcing data for daily precipitation and daily mean air temperature for each sub-basin were required. Statistical data required included initial nutrient pools in the soil, agricultural practices (i.e., manure and chemical fertilizer applications, crop husbandry, timing and amount of fertilization, sowing and harvesting), wet and dry atmospheric depositions of nutrients, and nutrient concentrations and outflow volumes of point sources from rural household, industrial and waste water treatment plants.

For model calibration and validation, discharge and in-stream nutrient concentration (inorganic nitrogen (IN), organic nitrogen (ON), total nitrogen (TN), soluble reactive phosphorus (SP), particulate phosphorus (PP) and total phosphorus (TP)) observed from one or several locations of the stream were used. Observations of internal hydrological variables (groundwater level, evapotranspiration and soil moisture) were also used for model parameter calibration and evaluation of model performance.

There are a relatively large number of hydrological and nitrogen process parameters required to be specified in the application of HYPE model (Lindström et al. 2010). Model parameters are sorted into general parameters, land-use dependent parameters and soil-type dependent parameters. For runoff simulation, most parameters reflect water holding characteristics, evapotranspiration rates, flow paths and recession rates. Considering nitrogen simulation, the model parameters describe processes of nitrogen transformations and sinks.

The baseline period includes effects of measures resulting from The National Programme for Construction of Urban Wastewater Treatment Plants (RBMP 2016) and The River basin management plans (2016-2021) (RBMP 2016), including measured which are currently implemented or that have been agreed upon in previous plans. The results of the modeling were compared with the baseline period of 2006-2014.

4.1. DISCHARGE MODELLING

For the daily discharge modeling in HYPE, two periods were selected from 2004-2014; a calibration dataset from 2004-2005 and a validation dataset from 2006-2014. Figure 7 shows the model performance results from validations of discharge in sub-basin 7 (the location of the gauging station in Wejherowo City) in the Reda catchment. The elements of the system are the Reda channel, waterway, and a weir which dams the water for a cement plant. Locations of sub-basins and gauging stations is shown on Figure 7.

Modelled discharge dynamics within the Reda basin were evaluated at the gauging station (sub-basin 7; Fig. 7). Generally, hydrodynamics in the Reda basin are characterised by rapid flow variations, higher discharges during the winter months, and low flow periods during summer. Total outflow of freshwater to Baltic Sea averaged over the simulated 30-year periods is presented in Figure 8.

4.2. NUTRIENT MODELING

In the case of the Reda catchment, difficulties in nutrient modeling were caused by an inconsistency between the location for flow measurements and those for water quality measurements. The longest time-series of observations for water quality is from the monitoring point called Reda Mrzezino, located below the mouth of the River Cedron, but this station has no flow monitoring. In contrast, the water gauge for calibrating the model in terms of discharge is located above the mouth of the River Cedron. As a result, some assumptions had to be made to use the results of quality measurements above the mouth of the River Cedron. Additional quality datasets have been obtained for sub-basin 2 (for 2011 only) and sub-basin 10 (2010 to 2014).

Projected climate change in WRF climate model predicted reduced daily concentration of N and P in the Reda catchment on average by 4.0% and 7.7%, respectively, compared to the baseline period (Fig. 9).

Projected climate change in RCA climate model predicted reduced daily concentration of N and P in the Reda catchment on average by 9.2% and 12.8%, respectively, compared to the baseline period (Fig. 10).

5. RESULTS

Results of the MIRACLE project delivered important information for present and future integrated water management. In comparison with the years 1967-2016, the average monthly air temperature during 2004-2014 was higher by 0.2 (October) to 1.1°C (July) in Lębork and Gdynia. On the other hand, the average annual precipitation for the period 2004-2014 was higher by 10.9 mm in Rębiska, 4.5 mm in Tępcz and 1.7 mm in Gdynia, and lower by 0.6 mm in Wejherowo.

For sub-basin 6531, the results of the RCA model according to the RCP8.5 scenario predict that in the period 2016-2045, the average monthly air temperature will change from –0.1°C in January to 18.4°C in July. On the other hand, using the WRF model for the same sub-basin and climate scenario, the monthly average air temperature is predicted to range from –0.1°C in January to 18.0°C in July and August. For sub-basin 6532, the results of the RCA model according to the RCP8.5 scenario predict that in 2016-2045 the average monthly air temperature will vary from –0.1°C in January to 19.1°C in July, while the WRF model predicts a change of –0.1°C in January to 18.9°C in July. The RCA model forecasts higher monthly average temperatures for sub-basins 6531 and 6532 from June to October, December and February. Moreover, in the period 2016-2045, an increase of annual precipitation in sub-basin 6531 is predicted for RCP8.5 by both models. The RCA model forecasts higher monthly precipitation totals for sub-basins 6531 and 6532 in February, March, June, July, September, October and December, compared to the WRF model for the RCP8.5 scenario.

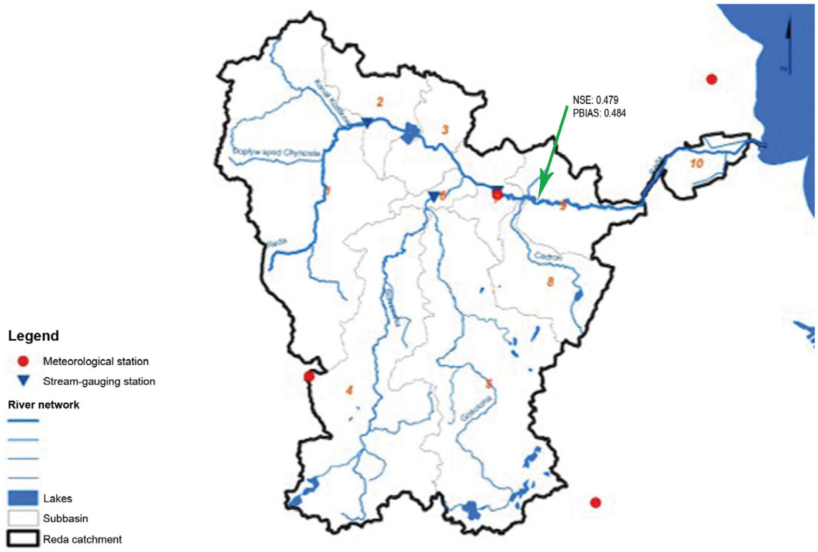

Fig. 7. Location of discharge gauging station in Reda River with HYPE model performance for baseline period 2006-2014 (NSE, PBIAS)

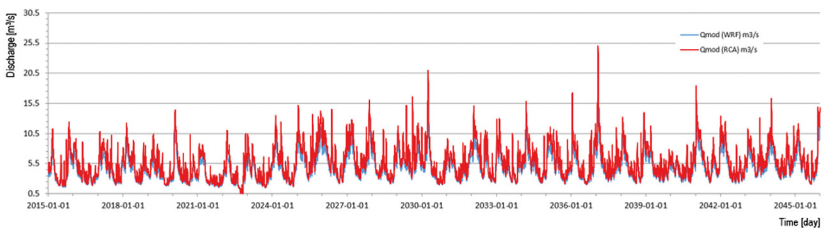

Fig. 8. Modelled discharge dynamics at the gauging station in the Reda River

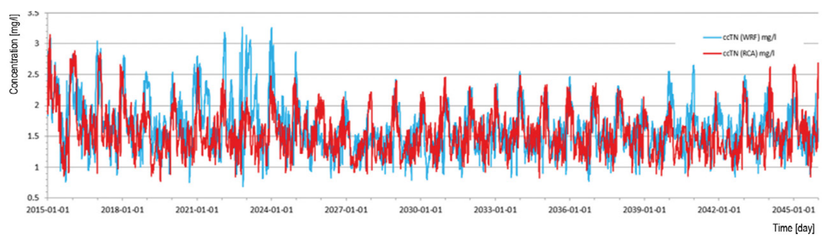

Fig. 9. Simulation of the daily total-N concentrations (mg/L) at the outlet of the Reda catchment for 2015-2045, using the WRF (blue) and RCA (red) models

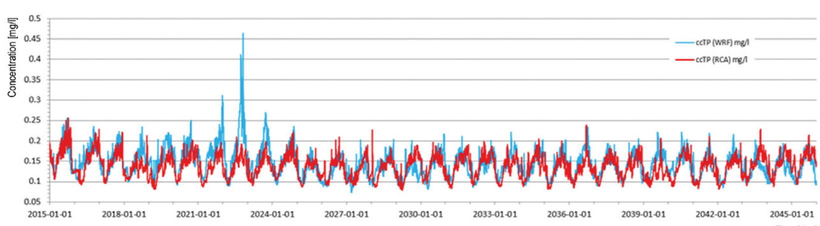

Fig. 10. Simulation of the daily total-P (mg/L) at the outlet of the Reda catchment for 2015-2045, using WRF (blue) and RCA (red) models

Results of modeling indicate a moderate increase of outflow from Reda catchment, averaging 14% and 18%, respectively for WRF and RCA regional climate models compared to the baseline period. However, the reliability of the model should be considered. In the case of the Reda catchment, difficulties in nutrient modeling were caused by an inconsistency between the location of water flow stations and those for water quality measurements. Projected climate change both in the WRF and RCA regional climate models predict a reduced concentration of N and P in the Reda catchment.

6. CONCLUSIONS

This study confirms that mathematical models are useful instruments in specifying detailed processes associated with water cycles in the environment and determining the interconnections and mutual relationships between them, as well as quantifying characteristic values for the assessment of quantity and quality of water resources, are a useful instrument. The models provide detailed information on the current and future structure and condition of water resources, including the impact of potential climate changes. Nevertheless, it should be mentioned that criteria for these models, for example use of appropriate data in the correct formats, as well as suitable model calibration is a challenging task, especially in the case of complex models. Future development of the water management sector should concentrate on specific local catchment areas, where application of the integrated water resources management principles and adaptation to climate changes will be more feasible and compatible with local spatial planning. To achieve the aims of the IWRM, a larger number and higher frequency of measurements are needed, in line with the requirements of the Directive 2000/60/EC based on IWRM and documents assessing the degree of its implementation (COM(2012)673 final). In Blueprint (COM (2012) 673 final), the thesis is clearly stressed that the cost of water monitoring is considerably lower than the costs of making incorrect decisions. The spatial scale of works required by the Directive 2000/60/EC focus on river basin areas rather than on individual catchments, where application of principles would be better linked with local spatial planning. At present, research and practice which are developing the concept of water resources management should consider inter alia, local conditions and climate change, to support adaptive water resources management. Adaptive management is defined as a systematic process of improving management by analyzing the effects of implemented water strategies, considering all uncertainties related to forecasts[7]. Therefore, the results of the project also developed conclusions for implementing the concept of adaptive water management in Poland, which can be used in strategic work and sectoral policies. The organizational structure of water resources planning should involve water administration representatives in the process of task implementation to a greater extent, so that their participation is not only limited to specifying and receiving project outcomes, but also includes their opinions[8]. The optimum in this respect would be to achieve such a balance in activities that will provide support for the planning process on the part of scientific units in the form of partial works, whilst also involving representatives of the administration in the formulation of final documents.

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