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WATER BALANCE COMPONENTS DURING RECENT FLOODS IN CROATIA

Komponente vodne ravnoteže tijekom recentnih poplava u Hrvatskoj

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Abstract: Water balance components according to the Palmer model were analysed for floods in Croatia in 2010, 2013 and 2014. A detailed analysis of water balance components (precipitation, loss, evapotranspiration, groundwater recharge and surface runoff) can reveal whether the flood originates from local precipitation or extreme precipitation, and/or snow melting that occurred elsewhere in the upper parts of the basin. According to the analysis described in the paper, abundant water in 2010, besides high local precipitation, came mainly from the upper parts of the basins, due to high precipitation in that area. A combination of large amounts of precipitation and rapid snow melting caused severe flooding in 2013, while favorable flooding conditions in 2014 are the result of long-lasting precipitation and soil saturation.

Key words: water balance components, floods, Palmer's water balance model

Sažetak: Analizirane su komponente vodne ravnoteže prema Palmerovom modelu tijekom poplava 2010., 2013. i 2014. godine. Detaljnom analizom komponenata (oborina, dovod iz dubine tla, evapotranspiracija, procjeđivanje i površinsko otjecanje) može se razlučiti da li su poplave nastale od lokalnih ekstremnih oborina ili oborine i/ili topljenja snijega na gornjim dijelovima sliva. Prema analizi opisanoj u radu obilna voda 2010. godine, osim od obilne lokalne oborine, došla je većinom iz gornjih dijelova sliva zbog obilne oborine i na tom području. Kombinacija velikih količina oborine i brzog topljenja snijega uzrokovala je poplave 2013. godine dok su uvjeti za poplave 2014. godine bili rezultat dugotrajne oborine i zasićenosti tla.

Ključne riječi: komponente vodne ravnoteže, poplave, Palmerov model vodne ravnoteže

1. INTRODUCTION

The catastrophic floods that have occurred in Croatia in the recent period have raised a need for a wider overview of the cause-consequence relationship in flood developing. In a changing climate, when flooding becomes more frequent and more intense, different analyses of past floods are useful for the development of mitigation and adaptation measures. Flooding during the autumn of 2010, beginning of 2013, and spring and autumn of 2014 has caused great economic damage to Croatia. Extremely rainy weather in 2010 (meteo.hr) caused floods over the whole of Croatia, while in 2013 and 2014 mainly continental parts were affected. In September of 2010 heavy precipitation in Slovenia and Croatia formed the highest Sava River water wave ever. A large part of the Turopolje region (part of the Sava River basin near Zagreb) was flooded and natural disaster was proclaimed. In the spring of 2013 snow melting coincided with large amounts of precipitation, and the Sava and Kupa River basins were flooded. The largest flood occurred in May of 2014 in Županjska Posavina (part of the lower Sava River basin), when the left river embankment broke and the Sava River flooded settlements.

Over the past few years floods have been analysed from different aspects and additional meteorological insights could help to better understand the cause-consequence relationship during floods. Kuspilić et al (2014) presented the most recent meteorological conditions during the floods in May of 2014. Bonacci and Oskoruš (2011) analysed hydrological safety in the Sava River basin and whether the safety of the city of Zagreb is in alignment with the new river conditions. Gajić-Čapka et al (2012) presented the damage caused by floods, including those of 2010, but only for the Croatian Adriatic coast. In this paper, Palmer's water balance model (Palmer, 1965) is used to give another perspective to recent floods. Water balance uses the principles of the conservation of water in a river basin, whereby any water entering a basin must be transferred into either evaporation or surface runoff, or stored in the ground (Žugaj, 2000). A few papers with analyses of Palmer's water balance components have been published, but none of them covered separate flood episodes (e.g. Gajić-Čapka and Zaninović, 2004; Pandžić, 1985). Although Palmer's water balance model is quite simple, it gives important insight into the amount of water which comes from precipitation and runs directly to river flows. The main goal of this study is to determine the meteorological factors that caused the observed floods, as well as the place of their origin (e.g. snow melting, heavy or long-lasting rain, local or upper part of the basin).

Originally, Palmer's method was developed for agronomy purposes; however, some calculated components are very useful for water management and flood assessment as well. Firstly, potential evapotranspiration can be used to estimate evaporation from the water surface, and secondly, surface runoff is basically water surplus that fills river flows. Thus, after precipitation occurs, evapotranspiration is the first process that uses water, followed by groundwater recharge, and finally water surplus runs off and fills watercourses. Surface runoff can be generated by infiltration excess. If it continues to rain and the soil is saturated (the maximum infiltration rate exceeded), surface runoff is instantly produced. The level of antecedent soil moisture is one factor affecting the length of time until the soil becomes saturated (Han, 2011). Flooding can occur if the amount of precipitation over an area exceeds the evaporation rate and infiltration ca-

Figure 1. Location of selected meteorological stations in the continental part of Croatia (white labels) and F analysed rivers (capital letters). (source: Google Earth)

Slika 1. Položaj odabranih meteoroloških postaja u kontinentalnom dijelu Hrvatske (bijeli nazivi) te analiziranih rijeka (velika slova). (izvor: Google Earth) pacity of the soil (Lin, 2012). Considering soil moisture is one of the most important conditions in the flood process, the analysis of Palmer's water balance components is a good way to gain different insights into flood development.

The methods and data used to calculate water balance components will be presented in the second section of the paper, followed by the results and the discussion. The main conclusions will be summarised at the end of the paper.

2. DATA AND METHODS

The data used in this study come from the measurements taken at 5 meteorological stations situated in the continental part of Croatia (Figure 1) over the period 2010-2014. The stations were chosen as representative by the availability of data in order to calculate water balance components for two larger basins, the Sava River basin and the Drava River basin, which include smaller basins like the Kupa and Mura River basin.

Water balance components were calculated using Palmer's water balance model:

$$P+L=ET+R+RO \quad (1)$$

where P is precipitation (mm), L is water loss from soil layers (mm), ET is evapotranspiration (mm), R is groundwater recharge (mm), and RO is surface runoff (mm) (Pandžić, 1985).

Precipitation is the only component that can be measured, while the other components can be calculated using meteorological parameters (mean monthly temperature, monthly precipitation sum, mean monthly relative humidity, and mean monthly wind strength). Pandžić and Vuković (1999) modified Eagleman's formula (Eagleman, 1967) for calculating potential evapotranspiration PET, i.e.:

$$\mathrm{PET} = C_t C_v C_s e_{\max}(100-U)^{1/2} \quad (2)$$

where C_t is the thermal constant, C_s is the solar constant, e_{max} is mean maximum water vapour pressure (hPa), U is mean monthly relative humidity (%), and C_v is the wind constant that can be determined from mean wind velocity or wind strength. Thus, the constant C_v can be calculated from:

$$C_v = 0.58 + 0.52v \quad \text{for } v \text{ in } ms^{-1} \quad (3)$$

$$C_v = 0.40 + 0.28v \quad \text{for } v \text{ in } Bf \quad (4)$$

As in previous studies, C_s (the solar constant) was set to 1.0 and C_t is calculated as described in Pandžić (1985). This calculus was used in numerous later studies (e.g. Gajić-Čapka and Zaninović, 2004, Zaninović and Gajić-Čapka, 2005, Zaninović and Gajić-Čapka, 2000). Groundwater recharge (R) and surface runoff (RO) are calculated from the sequence of conditions in the relations between the precipitation amount, potential evapotranspiration and the amount of water in the soil. A detailed procedure for calculating water balance components is described in Pandžić (1985).
The calculation of water balance components for the purpose of this paper starts in January 2010. According to Palmer's assumption that soil consists of two layers (20 cm and 1 m) and pedological data that 1 m of soil has the capacity of 400 mm of water in the continental part of Croatia (Pedološki institut, 1984), it could be assumed that in January soil saturation is at its maximum, and amounts to 80 mm of water in the first 20 cm of soil and 320 mm in the lower 1 meter of soil. Notwithstanding that the whole of Croatia was flooded in some years, the analysis of water balance components is presented only for two major river basins, with an emphasis on the years 2010, 2013 and 2014, when heavy flooding occurred.

3. RESULTS AND DISCUSSION

3.1. Floods in 2010

High precipitation that occurred in Slovenia as well in central Croatia in 2010 (Kratofil et al, 2011) caused severe flooding in both countries. During 2010 flooding appeared in autumn, mainly September, in all considered basins.

The Sava River basin in Croatia is presented with water balance components estimated for two representative locations: the Zagreb-Maksimir meteorological station (Figure 2a) and the Slavonski Brod one (Figure 2b). High water levels are not characteristic for September, but in September of 2010 severe flooding occurred in the Zagreb area. After June and July, when precipitation water was primarily used for evapotranspiration (PET>P), recharge occurred in August as identified by the calculation of water balance components at the Zagreb-Maksimir gauging station. September, when this flooding occurred, was characterised by a high precipitation amount and low potential evapotranspiration. A surface runoff of 29% of the monthly precipitation amount (194.7 mm), combined with water inflow from Slovenia, was sufficient to cause flooding in the Zagreb area. The water level in Zagreb reached 464 cm, which is, following 1964 (514 cm) and 1966 (486 cm), the highest water level in the history of measurements at this location. It should be noted that in those earlier years no relief channel was available; thus the water level in September of 2010 is considered the absolute maximum in the Zagreb area (Kratofil et al, 2011). The lower part of the Sava River basin is presented by the Slavonski Brod meteorological station, where no water surplus or high water level was determined in the autumn of 2010, due to low precipitation amounts in the right tributary basins of the Sava River (Kratofil et al, 2011).

The Kupa River is the largest Sava River tributary in Croatia. A precipitation deficit in the Kupa River basin occurred only in July of 2010 (as estimated at the Karlovac meteorological station, Figure 2c), while in other months high amounts of precipitation were recorded. During the summer month (August), precipitation water was used for evapotranspiration, and recharge occurred only in

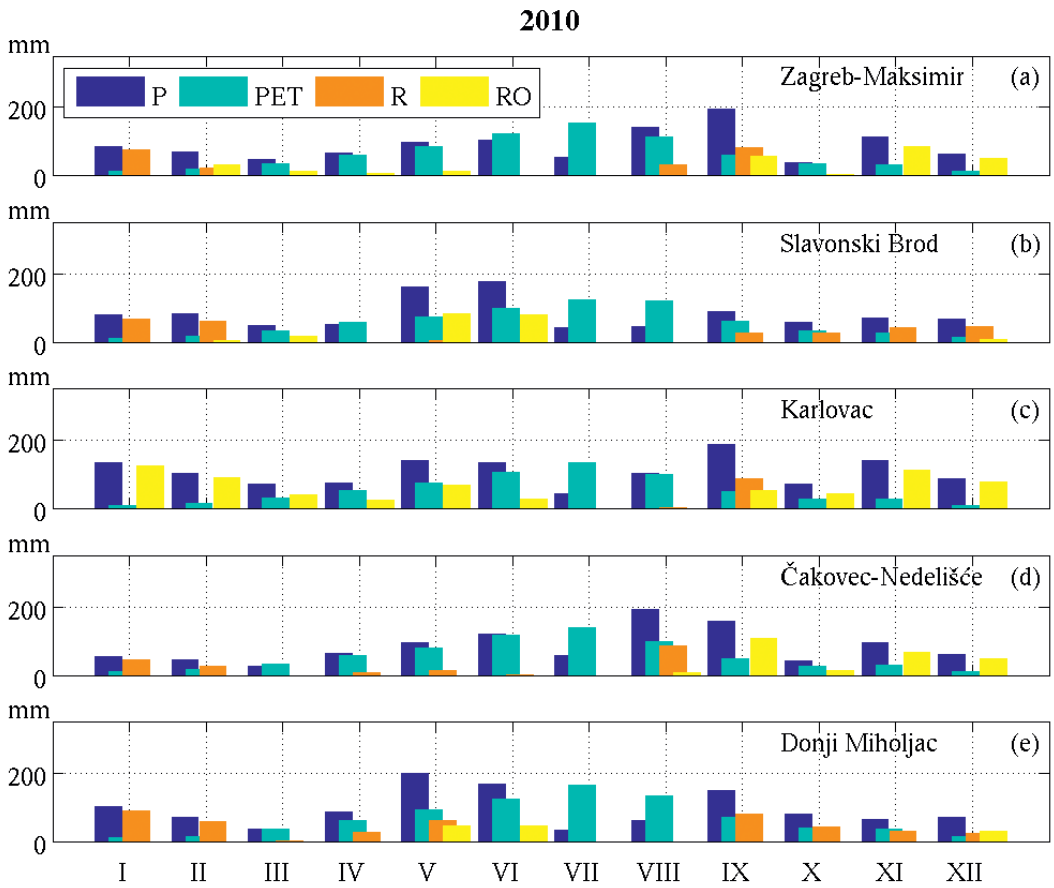

Figure 2. Water balance components in 2010 at 5 observed meteorological stations. P is precipitation, PET is potential evapotranspiration, R is groundwater recharge and RO is surface runoff.

Slika 2. Komponente vodne ravnoteže tijekom 2010. godine na 5 promatranih meteoroloških postaja. P je oborina, PET je potencijalna evapotranspiracija, R je procjeđivanje i RO je površinsko otjecanje.

September when the highest amount of precipitation at the Karlovac meteorological stations was recorded (187.2 mm). Thus, surface runoff was high during the whole year: between 21% in June and extremely high in January (93%). During the floods in the Kupa River basin in the autumn of 2010, surface runoff exceeded 62% of the corresponding monthly precipitation. The highest water level of the Kupa River (809 cm) occurred in December, which can, considering normal precipitation conditions at the Karlovac station (DHMZ, 2010), imply large amounts of precipitation and rapid snow melting during December in the higher parts of the Kupa River basin, in the region of Gorski kotar (Kratofil et al, 2011).

The Mura River is a large Drava River tributary and its basin is presented by Čakovec-Nedelišće meteorological station (Figure 2d). As is shown in the chart, a precipitation deficit in very rainy 2010 (meteo.hr) was detected only in March and July. In very rainy August (meteo.hr), when the precipitation amount reached 192.0 mm, the water was used for evapotranspiration and groundwater recharge, but a small amount of surface runoff also occurred. The largest surface runoff was detected in September (109.1 mm, i.e. 70% of the monthly precipitation amount), when the water level of the Mura River in Mursko Središće (a hydrological station at the Croatia-Slovenia border) reached 373 cm, but the Drava River and the Mura River did not endanger settlements (www.duzs.hr).

In the lower Drava River basin, presented by the Donji Miholjac (Figure 2e) meteorological station, the year 2010 was extremely rainy (meteo.hr). A precipitation deficit was evident only in two summer months (July and August). Although this year was extremely rainy, PET was not low implying high-intensity rain events; thus, on a monthly basis there was not enough water to saturate the soil and to produce a surface runoff. Only in May, June and December did some surface runoff occur, but with a low rate (22%, 26% and 45% of monthly precipitation respectively).

Considering water balance components, depending on meteorological parameters and soil characteristics, it can be concluded that flooding in the autumn of 2010 mainly occurred due to high local precipitation and large amounts of water that came from the upper parts of the basins.

3.2. Floods in 2013

At the beginning of 2013 floods occurred only in the Sava River (Zagreb area) and Kupa River basins.

At the Zagreb-Maksimir meteorological station (Figure 3a), the average PET value is low in winter months (Gajić-Čapka and Zaninović, 2004). At the beginning of 2013 precipitation amounts were relatively high (85.4 mm in February and 121.7 mm in March); thus, with low PET and high P the soil became saturated in February, which resulted in a high surface runoff rate in March (80% of the monthly precipitation amount). In the lower Sava River basin, in the region of Slavonija represented by the Slavonski Brod meteorological station, only recharge occurred during the winter months and no surface runoff was evident during the whole year (Figure 3b).

At the beginning of 2013, at the Karlovac meteorological station, high amounts of precipitation (between 159.5 mm and 230.6 mm) and low PET resulted in an extremely high water surplus in the Kupa River basin. During January, February and March, surface runoff was between 88% and 96% of monthly precipitation. Precipitation in the Kupa River basin was long-lasting and the soil was saturated. The high saturation of the soil could be noted from a high and continuous surface runoff in the beginning of 2013 (Figure 3c), which created conditions for the flooding of a large number of rivers and brooks. The Kupa River basin is also under the direct influence of snow melting in the upper part of the basin, i.e. in the region of Gorski kotar, which additionally created more prominent floods in March of 2013 (DHMZ, 2013). The flooding was probably caused by a combination of long-lasting precipitation in the previous months and the rapid snow melting and high precipitation in the region of Gorski kotar. In February the water level of the Kupa River in Karlovac reached 827 cm (www.voda.hr). Following the summer months (June, July and August) with a precipitation deficit, recharge was detected in September, and again in November when a high precipitation amount (209.3 mm) and low potential evapotranspiration enabled a recharge and surface runoff amounting to 58% of monthly precipitation.

In January and February of 2013, in the Mura River basin, precipitation was mainly used for groundwater recharge (Figure 3d) and no flooding occurred. A notable surface runoff was detected in March and it amounted to 78% of monthly precipitation, i.e. 77.9 mm. In April, in the summer months and in October a precipitation deficit was detected. The highest monthly precipitation amount, recorded in November (202.1 mm), was mainly used to compensate for the water deficit in the soil.

In 2013 surface runoff did not occur in the lower Drava River basin (Figure 3e). Although precipitation was higher than PET in the first three months of the year, and again in May, September and November, which followed its average annual course (Zaninović and Gajić-Čapka, 2000), only soil moisture recharge occurred and there was no surface runoff.

From a meteorological point of view, flooding in central Croatia in the early spring of 2013 was caused by a superposition of high precipitation, and thus soil saturation, and rapid snow melting in the region of Gorski kotar and the upper parts of the Sava and Kupa River basins in Slovenia.

3.3. Floods in 2014

In 2014 high water levels were recorded in all considered basins, except the lower Drava River basin. However, a catastrophic flood occurred in the lower Sava River basin in May, while in the Kupa and Mura River basins rivers endangered settlements in September.

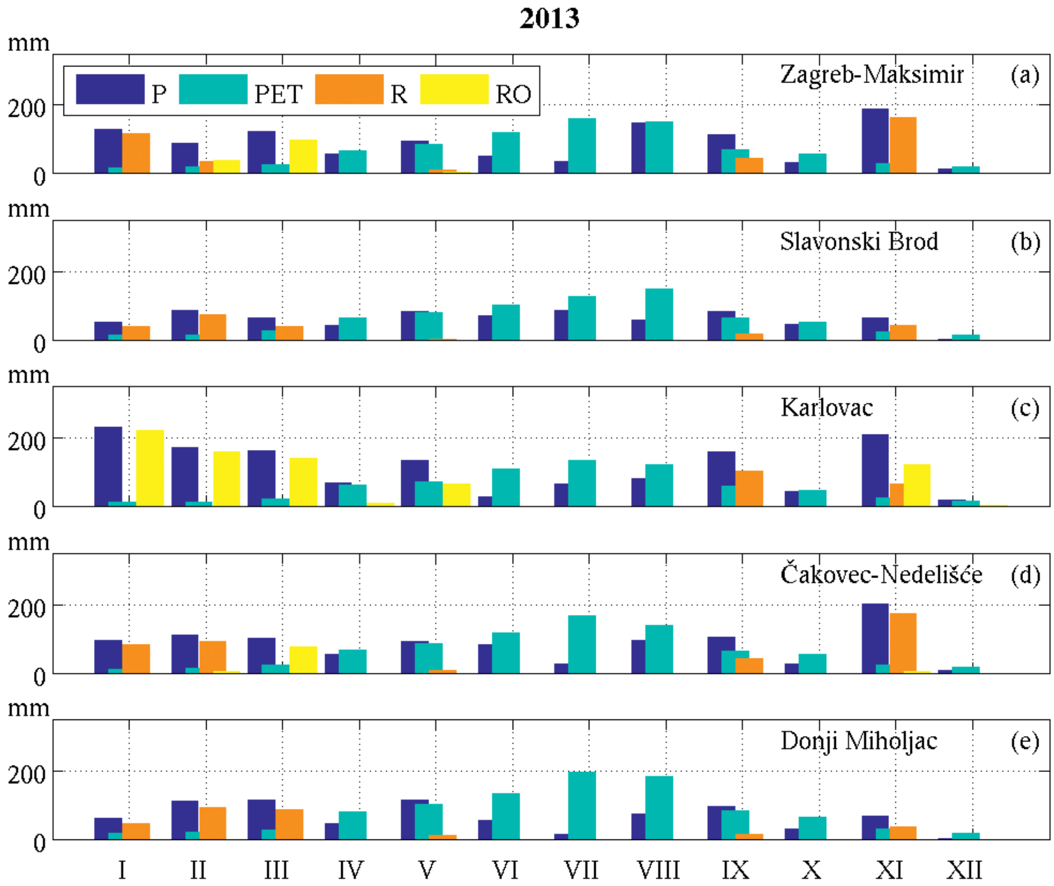

Figure 3. Water balance components in 2013 at 5 observed meteorological stations. P is precipitation, PET is potential evapotranspiration, R is groundwater recharge and RO is surface runoff.

Slika 3. Komponente vodne ravnoteže tijekom 2013. godine na 5 promatranih meteoroloških postaja. P je oborina, PET je potencijalna evapotranspiracija, R je procjeđivanje i RO je površinsko otjecanje.

Precipitation amounts higher than potential evapotranspiration were determined for almost every month of 2014 at the Zagreb-Maksimir meteorological station, except for March (Figure 4a). Recharge occurred in small amounts in January and from April to July, while surface runoff occurred every month except for March and April. Surface runoff was between 8% (August) and 85% (February) of the corresponding monthly precipitation amounts. It is important to emphasise that besides in February, runoff was over 60% of monthly precipitation from September to December. In the lower parts of the Sava River basin (the Slavonski Brod meteorological station, Figure 4b) high amounts of precipitation were recorded in April (119.0 mm) and May (133.8 mm). PET exceeded the rainfall rate only in June, July and November. A water surplus was detected in May (12% of the monthly precipitation amount), when great flooding occurred due to a river embankment break. The water wave was characterised as one with a 1000-year return period with an absolute water level maximum (Kratofil, 2014). Although there was no significant surface runoff in the lower Sava River basin, high precipitation amounts were detected in the middle part of the Sava River basin and a large amount of water continuously saturated the riverbanks downstream. Additionally, rivers from Bosnia and Herzegovina (the right Sava River tributaries, i.e. the Bosna, Una and Vrbas River) notably contributed to creating flood conditions (Kuspilić et al, 2014). Floods in the Sava River basin also occurred in September 2014. High surface runoff in the lower part of the Sava River basin (over 50% of the corresponding precipitation amount) occurred in October and again in December.

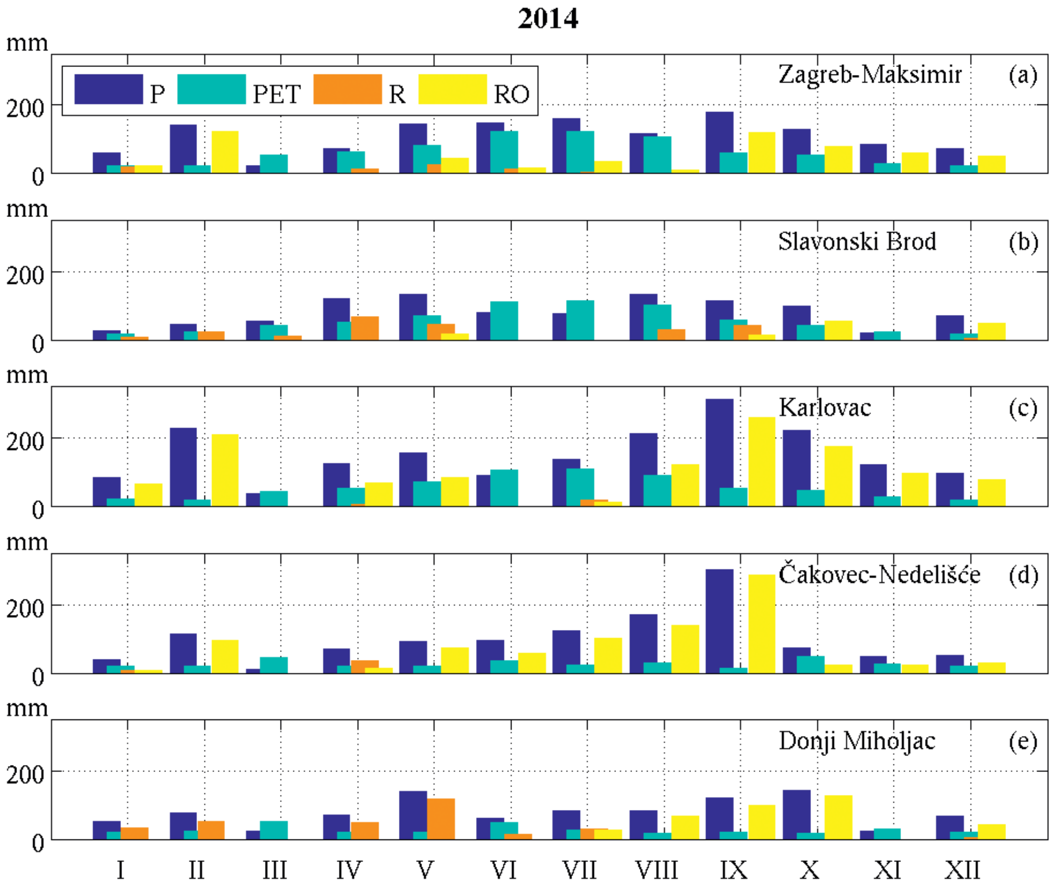

Figure 4. Water balance components in 2014 at 5 observed meteorological stations. P is precipitation, PET is potential evapotranspiration, R is groundwater recharge and RO is surface runoff.

Slika 4. Komponente vodne ravnoteže tijekom 2014. godine na 5 promatranih meteoroloških postaja. P je oborina, PET je potencijalna evapotranspiracija, R je procjeđivanje i RO je površinsko otjecanje.

Considering all three analysed years at the Karlovac gauging station, the largest monthly precipitation amounts were recorded in 2014 (Figure 4c). Precipitation in September was 311.2 mm, which is the largest amount recorded at all the observed meteorological stations in all the analysed years. PET exceeded precipitation amounts only in March and June, which resulted in the need for a small recharge in April and July. High precipitation amounts and low potential evapotranspiration during the winter led to high surface runoff, which in February reached 92% of monthly precipitation (225.1 mm) but with no high surface runoff in the previous months. Due to a high amount of precipitation in September, surface runoff was the highest in absolute values and it amounted to 259.4 mm, i.e. 83% of monthly precipitation. The highest Kupa River water level of 845 cm in Karlovac occurred on September 14, and the Korana River water level of 844 cm was measured the day before (Željeznjak, 2014). This implies soil saturation and a large amount of precipitation in that part of the basin, but not extreme precipitation in the upper parts of the basin (Renko, 2014).

Low PET and extremely high precipitation amounts (DHMZ, 2014) are the main characteristics of 2014 in the Mura River basin, implying low-intensity but long-lasting rain events (Figure 4d). The highest monthly precipitation amount was recorded in September (300.6 mm). A precipitation deficit was evident only in March and recharge was detected only in January and April; thus, the soil was saturated during the whole year. From April to December notable surface runoff occurred and the highest absolute values were detected in August (140.1 mm, i.e. 82%) and September (286.5 mm, i.e. 95%). In 2014, in the whole of the Drava River basin, especially in the Mura River catchment, the highest value of surface runoff coincides with September 15, when the highest water level of the Mura River in Mursko Središće amounted to 536 cm (Sekovanić, 2014).

After compensating for the water deficit in the soil in the first half of 2014 in the lower Drava River basin, a water surplus occurred in July due to P>PET, which persisted throughout the whole year (Figure 4e). High rates of surface runoff were detected from August to October (over 80% of the monthly precipitation amount) with the highest absolute value recorded in October - 126.6 mm - but there was no significant river response.

The main cause of flooding in 2014, according to the analysis of water balance components, was the water surplus that occurred as a consequence of low evapotranspiration and high amounts of precipitation in the lower parts of the basins, combined with water inflow from upstream tributaries.

4. CONCLUSION

This paper deals with the analysis of water balance components for floods in 2010, 2013 and 2014 in Croatia. The results enable us to distinguish whether flooding originates from local precipitation or extreme precipitation, and/or snow melting elsewhere in the upper parts of the basin.

Water balance components in the autumn of 2010 indicated high local precipitation together with high potential evapotranspiration; thus, it can be concluded that precipitation was of high intensity. In the upper parts of the considered basins (the region of Gorski kotar in Croatia and Slovenia) high-intensity precipitation also occurred. The water wave that came from the upper parts of the basin, together with the smaller contribution of local surface runoff, caused flooding.

In 2013 high precipitation and soil saturation in first three months resulted in high amounts of surface runoff. Moreover, in March there was rapid snow melting in the region of Gorski kotar and in the upper parts of the basins in Slovenia. Thus, a superposition of these two effects resulted in heavy flooding in central Croatia.

In 2014 the main characteristic of water balance components by month was water surplus as a consequence of low evapotranspiration and high amounts of precipitation. This was especially notable in the eastern parts of the Drava and Sava River basins. Low PET and high precipitation amounts indicated long-lasting rain events and maximum soil saturation, which, combined with abundant water inflow from the right Sava River tributaries, resulted in a catastrophic flood in the Županjska Posavina region (the easternmost part of the Sava River basin in

Croatia) in May. In autumn large amounts of precipitation fell on the soil that was already saturated; thus a high amount of surface runoff was produced, contributing to flooding.

Recent floods, although quite different in origin, were severe; thus they initiated investigation into and improvement of the existing flood protection system, taking into consideration all the influential factors, including the possible consequences of climate change. Considering climate change projections, an effort must be made to better understand, mitigate and adapt to new conditions; thus, by analysing water balance components, additional information is retrieved in order to accomplish these goals and assess the causes of recent floods.

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