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Sustainable energy production and resilience towards floods by using hydro and solar photovoltaic energy

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Abstract:
Unexpected and intense floods have become more frequent recently; this is related to extreme weather events that are difficult to predict accurately. This necessitates new solutions to decrease the risk of flooding urban and rural areas. Moreover, such solutions should have negligible impact on the environment. There are several concepts, tools, and technical measures for preventing floods, one of which is the 'monkey cheek' concept for flood protection, used in Thailand for protection from river and sea floods. Monkeys collect food in their mouths and eat subsequently in stages. In a similar manner, excess water from floods could be collected and stored in reservoirs, sags, canals, floodplain forests, and unused space. Collected water could then be used for irrigation. In most cases, collected water must be pumped to distant or higher locations compared to the location where the water was collected. This requires electric energy for the pumps. This paper analyses a case study for the presented concept for the town of Ludbreg in Croatia, currently undergoing real-site measurements and calculations. A rescaled adjusted partial sums method is applied for the analysis. It has been shown that the energy potential of the local, small river Bednja in the observed location could be approximated using the "monkey cheek'' concept. Within this, using the produced electricity from small hydropower plants and solar photovoltaic systems has been proven promising. The solution avoids building dams for flood protection, satisfying the environmental aspects.

Keywords:
monkey cheek; sustainable energy production; solar energy; hydro energy

1 Introduction

Flooding is a complex problem demanding novel solutions for mitigation and prevention, while satisfying the economic, ecological, and social needs of urban and rural areas. In other words, a holistic approach should be applied to the natural environment and engineering measures for flood prevention to achieve sustainable future development. Climate change, increasing human population, and energy needs have led to changes in natural hydrological cycles. One of the negative effects of these events is flooding. Several approaches, concepts, and guidelines related to floods are included in the strategies for mitigating the impact of climate change. These can be categorised as physical barriers and software packages that allocate and predict possible locations and times where floods can occur, such as in References [1, 2] etc.

Protection measures require preventing the negative effects on the environment, as well as fitting into the ecosystem, which is strongly emphasized in [3]. Five relevant principles are defined as follows. 'Principle 1': system-scale perspective; 'Principle 2': risk and benefit assessment of a full range of solutions; 'Principle 3': standardised performance evaluation; 'Principle 4': integration with ecosystem conservation and restoration; and 'Principle 5': adaptive management''. Principle 1 relates to nature-based solutions for climate change adaptation and disaster risk reduction. The first step was a system-wide analysis of local socioeconomic, environmental, and institutional conditions. Principle 2 involves a thorough assessment of the risks and benefits of the full range of possible measures that should be implemented. Such assessments cover risk reduction benefits as well as social and environmental effects. Principle 3 describes nature-based solutions for flood risk management that should be tested, designed, sized, and evaluated using quantitative criteria. Principle 4 states that nature-based solutions for flood risk management should include existing ecosystems and native species. These solutions should comply with the basic principles of ecological restoration and conservation. Principle 5 states that nature-based solutions for flood risk management require adaptive management based on long-term monitoring. This ensures sustainable performance. The principle of using renewable energy for flood protection is presented in [4], where gray, green, and blue design criteria were presented. The general principle of gray design is to mitigate storm damage, that is, flooding. Green design implies retaining existing ecological conditions, whereas blue design considers the application of renewable energy.

The 'monkey cheeks' concept presents a natural or constructed underground or surface space as a temporary flood storage area, as shown in Figure 1 [5, 6]. The term 'monkey cheek,' or 'kaem ling' in Thai, is used for artificial and natural flood protection projects in Thailand, especially in Bangkok. This is an analogy with the behaviour of monkeys where they generally collect food in their mouths and subsequently eat in stages; floodwater is also stored in some areas and released afterwards. Thus, the concept of a monkey cheek is similar to that of a detention pond or basin. This means that flood management in the area has been designated to retain floodwater during rain or flood events. It also involves retention ponds that store and drain floodwater into the monkey cheek system instead of along the streets and roads of cities. Monkey cheek areas can become wet and dry at different times. Dry basins retain water only during storm events and release it for specific purposes until they are empty. The Monkey cheek project in Bangkok and its metropolitan areas was primarily conducted by excavating the canals along the coastal regions west and east of the Chao Phraya River, as shown in Figure 1. These coastal zones have served as large detention ponds or monkey cheeks, and have drained floodwater by natural means such as gravity or tidal flow. The monkey cheek of Western Chao Phraya River is managed by the Tha Chin River, a river near the east. Floodwater is released through the canal system into the Tha Chin River and eventually into the Gulf of Thailand. The monkey cheek of the Eastern Chao Phraya River has been managed through the canal system in the area, which functions as a detention basin. Detailed insights are presented in Figure 2. Examples of the monkey cheek concept are presented in Figures 3 and 4.

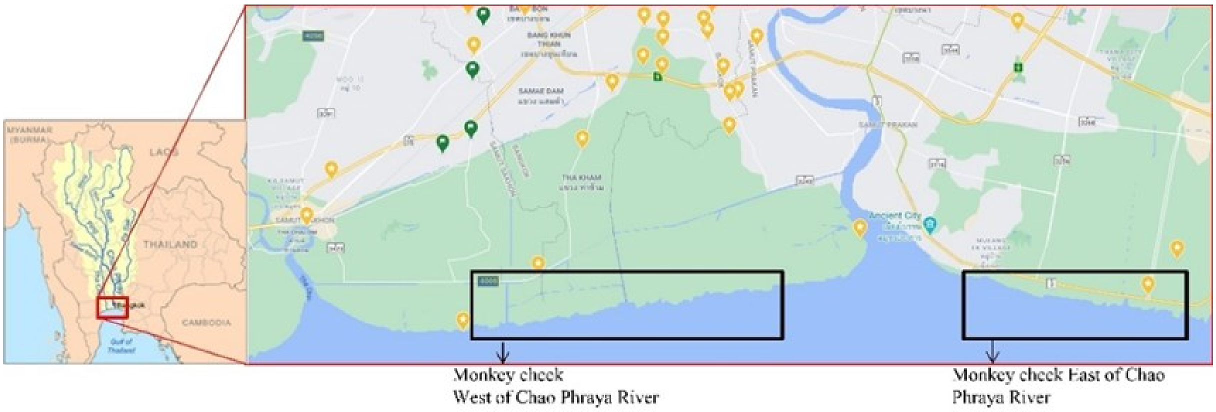

Figure 1. Sketch of monkey cheek in Bangkok and nearby areas [7]

Figure 2. Detailed insight into the Bangkok case study [7]

Figure 3. "Monkey cheek" concept as an opportunity for recreation [7, 8], Davidson's mill pond park

Recently, monkey cheek projects have been extended to other areas of Thailand to solve flooding problems. The Nong Yai Area Development Project in Chumphon Province, Southern Thailand, is an example of a realistic monkey cheek project serving communities in Chumphon Province. Nong Yai can store up to 3 million m3. Systems/series of monkey cheeks are designed to collect and release floods in southern Thailand along the Lower Chao Phraya

River. These areas are called Bang Ban, Pak Hai, Phraya Banlue, and Pho Phraya, respectively, and are used to store water for other purposes such as fisheries. Water flow requires water pumping and energy for operation work of water pumps not only for the monkey cheeks, but also for all other flood protection concepts. Hydro energy and solar energy are very promising renewable energy sources considering their operability and availability [8, 9]. It can be concluded that a hybrid system comprising a mini-hydropower plant and solar photovoltaic power plant can serve as the source of electrical energy required for the functioning and sustainability of the proposed concept for flood prevention. Hence, the produced electrical energy can be used for water pumping and distribution during floods or enlarged flow (water level), lighting, infrastructure objects, intelligent benches, etc.
The analysed area of Ludbreg in Croatia was naturally influenced by past floods. Subsequently, there was significant regulation work to extend the cross-section and clean the river trough from vegetation. Unfortunately, the negative consequences of climate change are also reflected in precipitation, and consequently, in river flows. This frequently leads to extreme weather conditions that are difficult to predict. This has motivated the application of new solutions and concepts for flood protection, one of them is the “monkey cheek” concept using hydro power and solar photovoltaic energy within the hybrid energy system. Considering future practical application in projects, this study will provide insights into flood management with the possibility of producing green electrical energy.

2 Sizing of the elements of the energy and water hybrid system

The average power of a solar photovoltaic (PV) system, PPV (W), can be calculated using [10]:

$$P_{PV} = A \cdot \eta_{PV} \cdot 1000 \tag{1}$$

where *A* is the area of the PV panels (m^2) and η_{PV} is the efficiency of the PV system. The power of the hydropower plant $P_{HP,P}$ can be calculated as [11]:

$$P_{HP,P} = \rho \cdot g \cdot Q_{HP} \cdot \Delta H \cdot \eta_{HP} \tag{2}$$

where ρ is the water density (1000 kg/m^3), g is the acceleration of the gravity (m/s^2), QHP is the measured daily average flow rate (m^3/s), ΔH is the difference in hydraulic head in analysed water course segment (m), and η_{PV} is the efficiency of the hydropower plant. In addition, the power of the hydropower plant $P_{HP,K}$, where turbines use the kinetic energy of water, can be calculated as [12]:

$$P_{HP,K} = \xi \cdot \frac{\rho}{2} \cdot v^3 \cdot A_r \tag{3}$$

where ξ is the hydro powerplant efficiency, *v* is the velocity of the water, and A_r is the devices' frontal (or swept) area (m^2).
The proposed flood protection concept involves using and installing flow pump(s) without accumulation reservoirs to minimise the impact on the environment. It should also be noted that small hydropower plants with turbines of up to 10 MW, or even micro hydropower plants with turbines of 5 to 100 kW have a negligible environmental impact, irrespective of their design (accumulation reservoir and partition for rising water level). The power of the water pump can be calculated as [13]:

$$P_{PS} = \rho \cdot g \cdot \Delta Q_{PS} \cdot H_{PS} \cdot \eta_{PS} \tag{4}$$

where ΔQ_{PS} is the required/adopted flow amount (m^3/s) for water pumping and η_{PS} is the pump's efficiency (%). The rescaled adjusted partial sums method (RAPS) is based on a time-series analysis using the deviation sum curve. A series can be detected by visualising the RAPS method, small systems, and random errors over time. The visual presentation of the RAPS method often reveals the existence of subseries with similar characteristics, significant scale trends, unexpected value changes, irregular fluctuations, and periodicity. The RAPS is defined as follows:

$$RAPS_k = \sum_{t=1}^{k} \frac{Y_t - \bar{Y}}{S_y} \quad (5)$$

where *Σ* is the average value of the entire time series, S_y is the standard deviation of the same series, *n* is the amount of data in the time series, and *k* is the summation counter (k=1, 2, 3, …, *n*) [14].

Visual presentation of the $RAPS_k$ values provides insight into the regularities in the fluctuations of the analysed parameters (Y_t) [15]. The process of determining a new subseries is based on visual determination, that is, identifying the highest "peak'' or lowest "valley'' on the RAPS diagram. Regarding solar photovoltaic power plants, it is essential to note that they are significantly easier to instal and adjust (especially panels) than turbines. By adding or removing PV panels, the power and electric energy production can be increased or decreased. PV panels can be placed on the roofs of objects such as eaves or in unused or neglected areas. In general, the produced energy $E_{prod,t}$ during period t can be written as:

$$E_{prod,t} = \sum_{i=1}^{n} E_{HE,Q,i,t} + \sum_{j=1}^{n} E_{HE,v,j,t} + \sum_{k=1}^{n} E_{PV,k,t} \quad (6)$$

where $E_{HE,Q,i}$ is the energy produced from the turbines that use the potential energy of water; $E_{HE,v,j}$ is the energy produced from the turbines which use the kinetic energy of water; $E_{PV,v,k}$ is the energy produced by the solar photovoltaic system; and *i*, *j*, and *k* are the numbers of turbines and solar panels of the relevant sizes, respectively, all at the analysed time *t*.

3 Methodology

The first step was the theoretical presentation of the manner of the flow during the observed year(s), as shown in Figure 4.

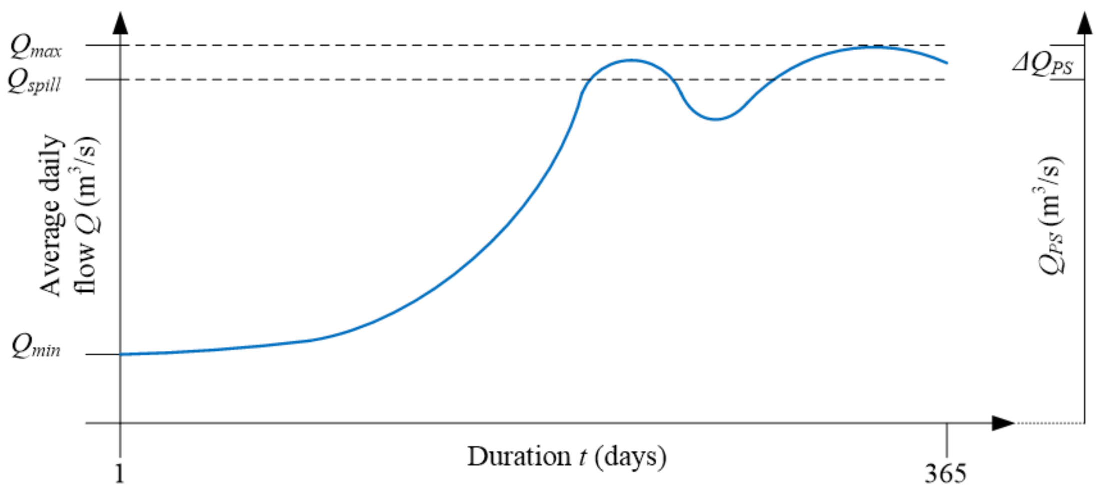

Figure 4. Theoretical presentation of the flow balance in the water course

It is necessary to define the spillway flow Q_{spill}, which is the amount of water that spills out of the trough of the river or watercourse in general. Q_{spill} is generally calculated for the analysed area/part of the watercourse and depends on the geometrical characteristics of the trough. Turbine installation uses the potential energy of the flow; in situations where a partition (bulkhead) is constructed, an increase in the water level must be considered because of the upstream slowdown. ΔQ_{PS} is the energy required water to pump the spilled water surplus, which should be pumped from the watercourse to avoid flood. The pumped water is distributed in natural or artificial depressions, pools, ponds, lagoons, lakes, floodplains, etc.

Q_{min} and Q_{max} are the minimum and maximum values of the measured daily average daily flow in the characteristic year with their corresponding durations of one day and 365 days, respectively. If the flow volume is larger than the nominal flow value (the value of which is the turbine size, Q_{req}), this amount of water does not enter the turbine; that is, it cannot be used for turbine work, because the surplus does not pass through the turbine. A flow smaller than Q_{req} cannot be used, because it is too small to enter or pass through the turbine.
RAPS analysis was applied to the time series of daily average flows over a duration of 10 years, averaged daily flows over a scale of one year, and averaged insolation, all for the analysed location of Ludbreg. The last stage of the analysis involved calculating the sizes of the parts of the presented concept.

4 Results and Discussion

The monkey cheek concept is applied to a real location in the town of Ludbreg, in the north-western part of Croatia (Figure 5). on the Bednja River flows. Despite the arrangement and widening of the riverbed at the analysed location, the possibility of overflow is always present. This is especially emphasised by slowdowns that can occur due to waste disposal in the river, branches, debris picked up by tributaries within the river basin, sediment, and unregulated parts of the river. Climate change is also one of the causes of extreme rainfall, and therefore, increases the river flow.

Figure 5. The geographic position of the town of Ludbreg [16]

Figure 6. Location of the hydrological measurement station Ludbreg on the river Bednja

Figure 7 shows one possible implementation of the monkey cheek concept. The aim is to pump and transport all of the overflowing water through pipelines, with final deposition on the forest terrain. In addition, part of the overflowed water can be displaced in ponds, which are artificial (built) in most cases, but are fitted in some cases into the existing environment. Natural hollows and lowlands could also be used for this purpose (Figure 8). Water pumps are located on both coasts of the Bednja River, and the pipelines are situated underground. The energy system (energy power plant) comprising a small hydropower plant and solar photovoltaic power plant, produces electric energy that can be used for all the aforementioned purposes.

Figure 7. Suggestion of the facilities and objects of the monkey cheek concept of flood prevention

Figure 8. Downstream side view of the available locations at both riverbanks for temporary storage of the pumped water

The surrounding area is urbanised (Figures 6 and 7). However, free unused spaces are available; in addition to natural depressions, bushes, and trees, which could be used for the storage of excess (overflow) water, as shown in Figure 8. Moreover, ponds could be constructed as additional water retention systems, which could nicely be embedded into the ambient environment. There are several possible solutions for retaining water surplus, even in underground reservoirs, if usurpation of the surface area is impossible.

Figure 9 shows the distribution of total daily precipitation for the town of Ludbreg for a period of ten years (from 2008 to 2017) [17]; Figure 10 shows a hydrogram for the same period for the Bednja River at the hydrological station Ludbreg [18] which is under the bridge shown in Figure 5, while Figure 9 shows an averaged hydrogram for the ten years.

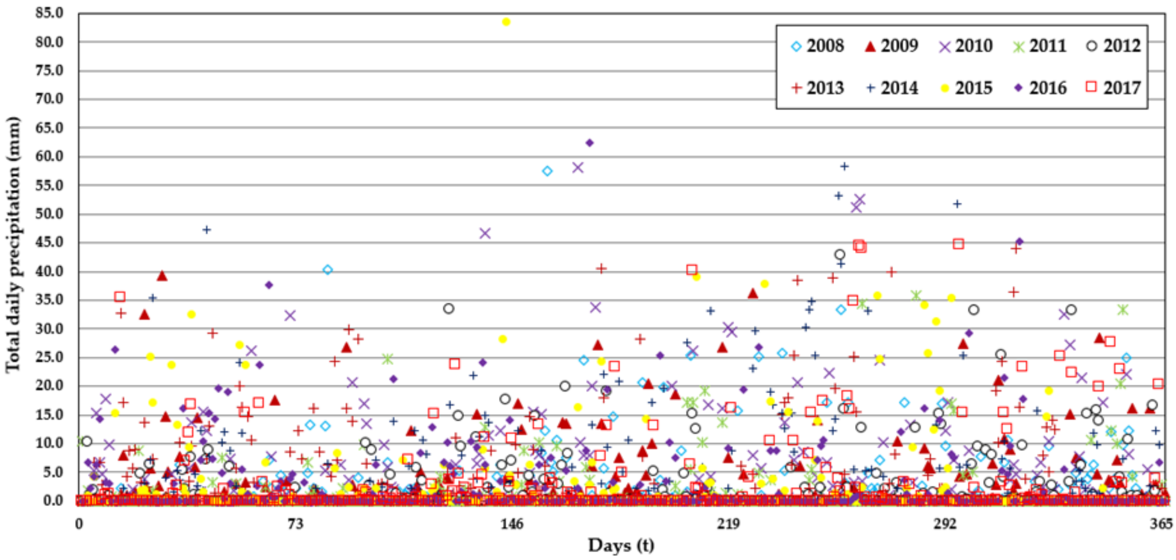

Figure 9. Distribution of the total daily precipitation for the city of Ludbreg for a period of ten years (2008-2017)

There were significant differences in the actual precipitation values for the analysed period, from 0 to a maximum of 83,60 mm in 2015. The average daily flow was also variable, from a

minimum of 0,914 m^3/s in 2012 to a maximum of 116 m^3/s in 2014. The driest years in terms of precipitation were 2011 and 2012, which were also reflected in the daily river flows. Precipitation has a stochastic nature each year and average daily flow. It should be emphasized that river Bednja has torrential characteristics. Flows notably increased within a couple of days after precipitation and then decreased in the same manner.
The averaged hydrogram in Figure 11 does not exhibit such significant deviations (minimum 1,569 m^3/s on the 226th day and maximum 21,039 m^3/s on the 264th day) compared with the values within ten years shown in Figure 10.

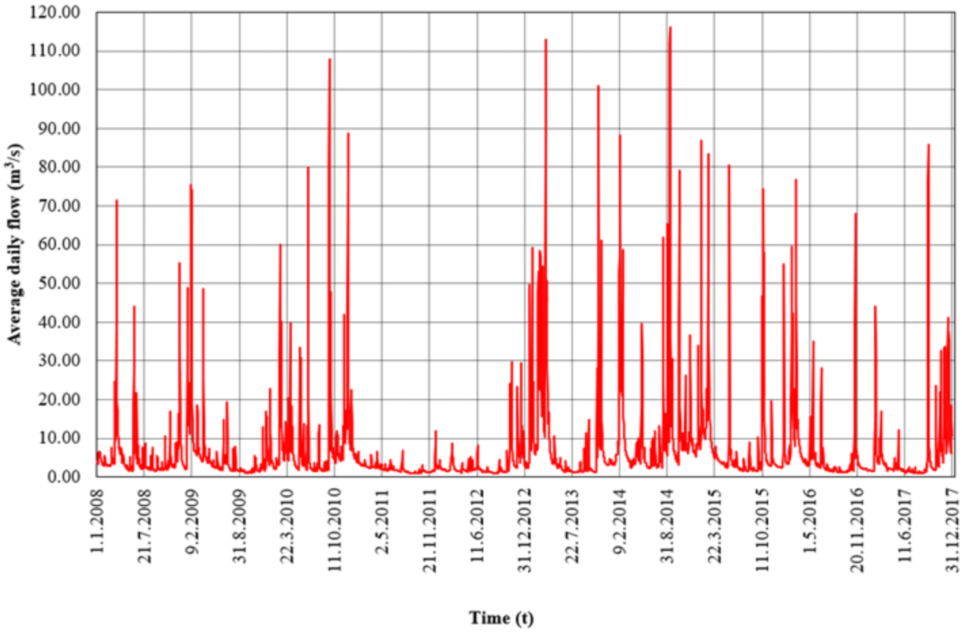

Figure 10. Hydrogram of the river Bednja for hydrological station Ludbreg for ten years (2008-2017)

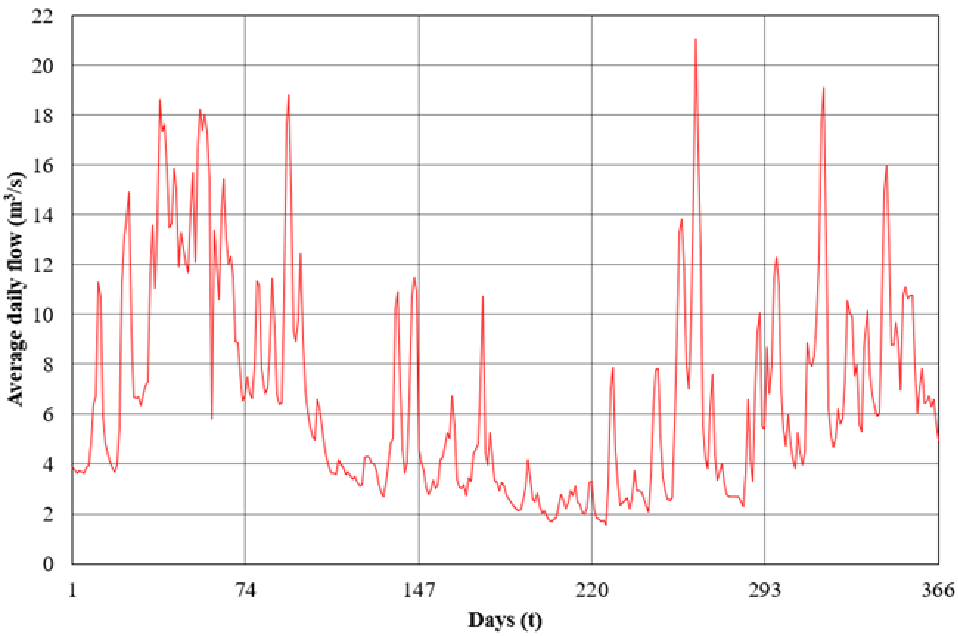

Figure 11. Hydrogram of the river Bednja for hydrological station Ludbreg for an average period of ten years (2008-2017)

It is impossible to predict periods when extreme values, that is, the possibility of overflow, could be expected. This is particularly important because of the stream characteristics of the Bednja River. After the precipitation period ended, all increased water inflows from tributaries and channels, inflows from the catchment areas, and inflows from sewage systems entered the Bednja River. Such extreme events can be mitigated by applying the concept presented in this study. Figure 12 shows the global insolation values for the town of Ludbreg for the average characteristic year at the analysed location, obtained using the free online application PVGIS [19].

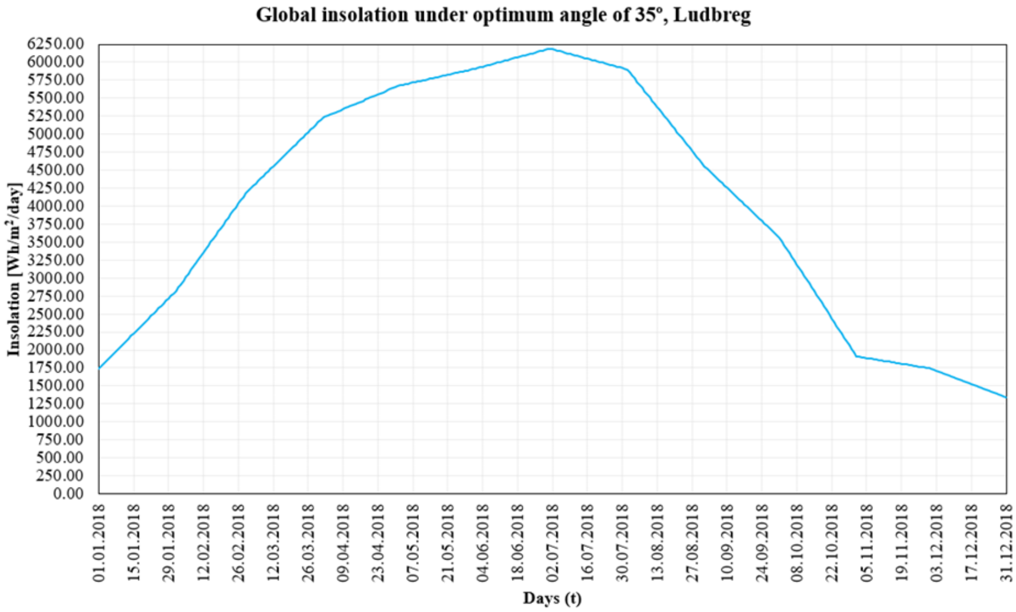

Figure 12. Averaged global insolation values for Ludbreg for the year 2018 under optimum angle of 35°

An optimum angle of 35° was obtained by applying the PVGIS, while the solar panels were oriented on the southern side. During summer, the insolation was the largest, which was expected.As stated earlier, insights into the seasonal characteristics of flow and insolation changes will aid in understanding their behaviour, that is, prepare for possible changes in their values. Applying the RAPS method, that is, Equation (5), to the hydrograms in Figures 10 and 11, the original time series are split into new subseries, as shown in Figures 13 and 14.

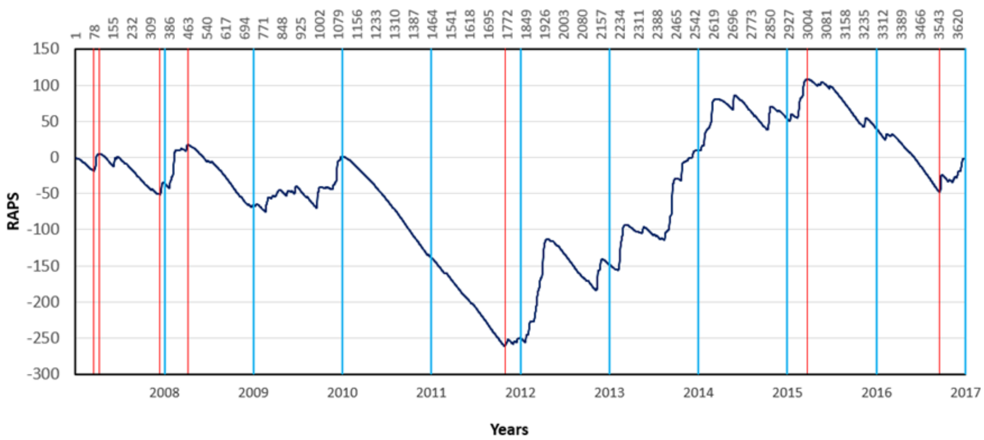

Figure 13. Application of the RAPS method on the hydrogram of river Bednja at measuring station Ludbreg for years 2008-2017

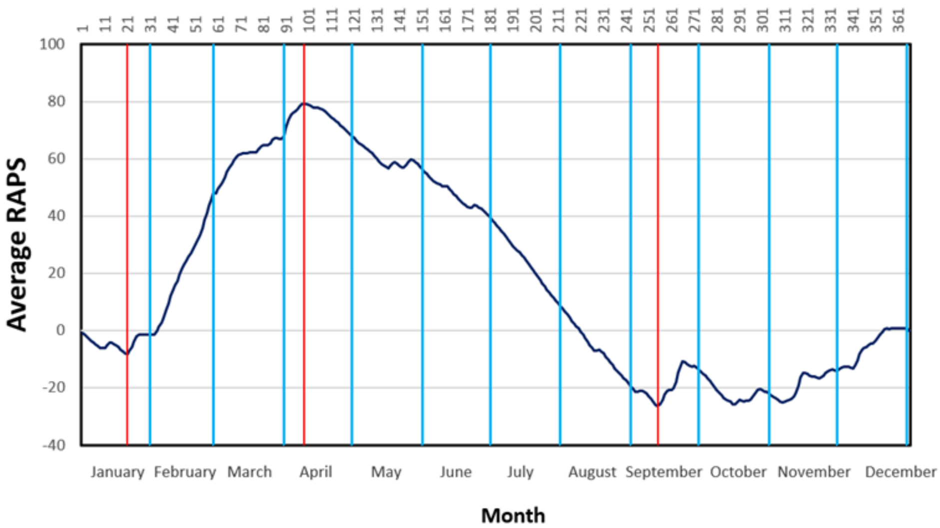

Figure 14. Application of the RAPS method on the hydrogram of river Bednja for averaged values of years 2008-2017

Three major subseries were identified in this study. The first period was from the beginning of 2009 to the end of 2012. The second subseries spans from the end of 2012 to the end of 2016. The lengths of the subseries at the beginning and end of 2008 and the end of 2017 are attributed to the interruption of continuity due to considering the analysed subseries for a duration of 10 years.

Applying Equation (5) to an averaged year shows three subseries dominant periods throughout the year, as shown in Figure 14. The red vertical lines represent the borders within the newly obtained subseries, whereas the blue vertical lines represent months.

The period from March to September (the middle period of the year) has a lower average daily flow value. Period(s) beyond the above-mentioned period are characterised by larger average daily flows compared to the middle period of the year.

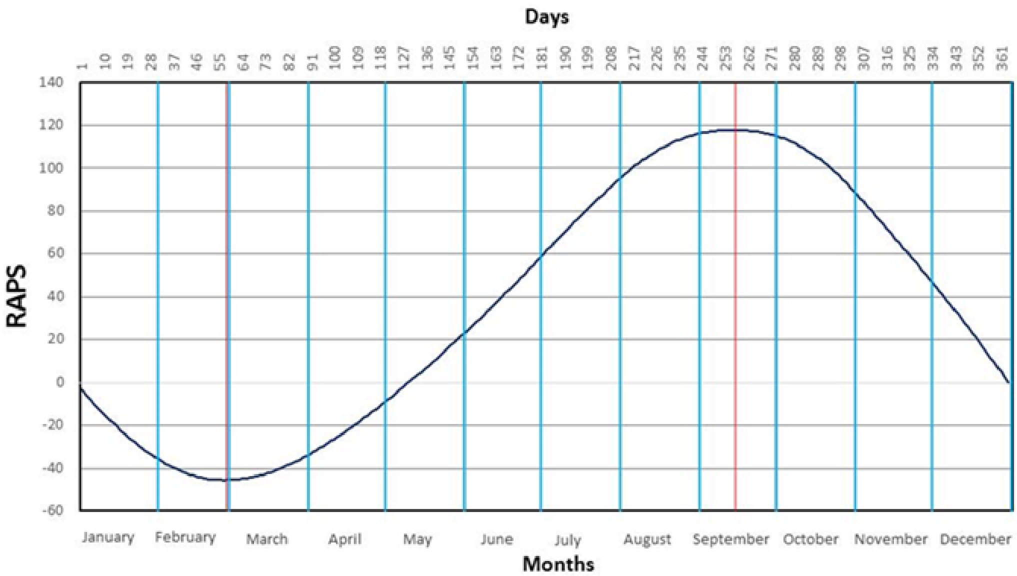

Figure 15. Application of RAPS for an averaged global insolation value for Ludbreg for analysed year

The RAPS method was also applied to the average global insolation values for Ludbreg (Figure 12). The RAPS values in Figure 15 overlap with the observed periods. Here, the opposite trend

is noted. In other words, insolation was largest during the period from March to September, compared to the average daily flows, and vice versa.
Application of RAPS showed that during parts of the season, increasing river flow and insolation, that is, decreasing river flow and insolation, could be expected. In addition, this indicates an inverse overlap between hydro energy and solar photovoltaic energy throughout the year; that is, the acceptability of using these energy sources.
To determine whether the maximum flowing water will spill out of the Bednja River at the analysed location, the water depth must be calculated. To this end, a reconstruction of the depth was be performed using a cross-section of the watercourse at the observed limnigraph station, together with values of the average daily flow, which can be seen in Figure 10, as well as the values of the average daily water levels obtained from [19].
The water depth in the watercourse was calculated based on the lowest point of the river bottom. Owing to sedimentation and erosion, the river bottom (depth) changes. In other words, it is difficult to determine the depth accurately. Nevertheless, at this level of research, the obtained values met the requirements of the calculations and typical hydrotechnical rules.
Regarding the maximum average daily flow Q_{max} = 115,80 m^3/s, which occurred during the analysed period of 10 years (Figure 10), after reconstruction of the depth *H* from water level L_W, the corresponding depth of the water is 3,38 m, as shown in Table 1. It can be seen that the water for the specified flow does not spill over the riverbed, that is, the watercourse ($Q_{max}<Q_{spill}$, Figure 1). In this case, water pumping was not necessary, indicating that water pumps were not required at this location. The presented methodology should be tested at other locations, especially near the research area, owing to possible cross- and longitudinal-section profile changes.
The power of the turbines, which uses the potential energy of water, was calculated using Equation (1) and is presented in Table 1. In this calculation, the value of a water depth is in the function of a bulkhead of height *H*. Heights *H* are calculated concerning the lowest water level L_W = -0,41 m and Q_{min} = 0,91 m^3/s, until the highest L_W = 2,88 m related to the Q_{max} = 115,80 m^3/s. The adopted turbine efficiency is equal to 80 %, meeting recommendations [13, 20]. Between the lowest and the highest water level L_W, the calculation steps result in a 1,0 m difference to obtain better insight into the changes in the turbine power with respect to increasing heights of the bulkhead *H*.

Table 1. Insight into the potential power of the turbines concerning the potential hydro energy

L_W (m)	*H* (m)	*Q* (m^3/s)	$P_{HP,P}$ (W)
-0,41	0,09	0,91	645,58
0,00	0,50	4,45	17.453,95
1,00	1,50	28,65	337.267,80
2,00	2,50	64,42	1.263.920,40
2,88	3,38	115,80	3.071.738,59

It is noticeable that the larger the height of the bulkhead, the higher the turbine's power. Additionally, it is theoretically possible to combine, for example, Q_{min} = 0,91 m^3/s with H_{max} of 3,38 m, where the output power of the turbine would be 24.138,88 W. However, due to the installation of a barrier, any increase in the water level could cause a downstream slowdown, which especially occurs with water waves. Such slowdowns can be negligible, but can also cause overflow. A possible solution for increasing the power of the turbines is to place the turbines and bulkheads in series at a certain distance from each other.
In the same manner, using Equation (4), the turbine's velocity and potential, which use the kinetic energy of water, were calculated and are shown in Table 2.

Table 2. Calculations of the potential power of the kinetic hydro turbines

L_W (m)	H (m)	A_r (m^2)	Q (m^3/s)	v (m/s)	$P_{HP,K}$ (W)
-0,41	0,09	1,01	0,91	0,90	110,44
0,00	0,50	3,75	24,45	1,19	947,90
1,00	1,50	24,10	28,65	1,19	6.091,85
2,00	2,50	43,00	64,42	1,50	21.768,75
2,88	3,38	111,00	115,80	1,04	18.728,99

Owing to their small velocities, the calculated powers are negligible compared to those of turbines that use potential water energy. In addition, the entire cross-sectional area of the river could not be used for the operational work of the kinetic turbines. However, this premise is satisfactory at the present level. In addition, compared to turbines that use the potential energy of water, an increase in the power of turbines is achieved by the placement of turbines and bulkheads in series and parallel at a certain distance from each other. The advantage of kinetic turbines over those that use the potential energy of water is that water deceleration does not occur. A disadvantage of kinetic turbines is that their watercourse speeds must be as high as possible.

Regarding the power of solar PV systems, as shown in Figure 6, space is available illation. If a PV system can be constructed, it will be in the form of eaves from one bank of the river to the other side, or parallel to the river. The calculated area was 98,4 m^2 (47,2 + 1,0 m on each side × 2 m in the direction of the river, which is 49,2 × 2,0 m) [8]. Furthermore, the panels were located either parallel to the river course, within the riverbank, or closer. By using Equation (1) and an efficiency of η_{PV} = 30 % [8, 21], the obtained power is equal to 20 kW for one eave.

5 Conclusion

This paper showed that the monkey cheek concept, combined with solar photo-voltaic and hydro energy, could be an efficient and attractive solution for preventing the negative impact of floods for the urban and rural areas. This avoids calculating the probability of occurrence of different water flows and depths, which is a trivial task considering climate change. The application of the RAPS method indicates the periods in a year in which attention should be paid to possible changes in the flow. Such differences cannot be observed in a typical review of hydrograms, precipitation, and precipitation diagrams.

In addition, the construction of dams and land usurpation are avoided, which is a significant advantage of this concept. A possible slowdown is also considered. The proposed solution is more favourable than the construction of a flood protection barrier.

Facilities, which are part of the presented solution, could aid in tourism development; for example, as a walking tour near the facilities, for recreation, educational trails, and bicycle lanes. The use of renewable energy is a promising prospect, particularly in rural and remote areas, owing to the lack of conventional energy sources. Any produced excess energy could be used for illumination, installation of smart benches, laptops, and mobile phone charging stations, etc. The proposed concept can also be used for amelioration purposes. Similarly, there is always the possibility of transferring excess electric energy to the settlement or industry itself.

This paper presents insight into the application of the monkey cheek concept, considering the Bednja river's hydropower potential and the site's solar photovoltaic potential as an example. This research can be continued and enhanced by measuring the geometrical characteristics of river profiles. In addition, a follow-up to this paper will analyse and consider the overall velocity and flow analysis for the river Bednja. The follow-up paper will present the energy and water balance, benefits and disadvantages of the proposed concept, and its impact on the environment.

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