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Ground Water Modelling for the Restoration of *Carex* Communities on a Sandy River Terrace

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Abstract: Management for sustainable river valleys requires balancing their natural values against the need for agricultural and recreational development on surrounding lands. The Southern Całowanie Peatland near the city of Warsaw sits on a sandy terrace and has well preserved *Carex* and *Molinia* stands existing in part of the area, especially where water tables are less than 1.5 m below the surface. The existing drainage network in this southern part has been poorly maintained and could be reestablished to help raise water levels for restoration of the peatland. Modflow was used to look at influence of drainage channel water levels on the overall water table height in the area. By raising water levels in the drainage system by 0.5 m it was found that 29% of the area would become suitable for increasing *Carex* and *Molinia* communities.

Keywords: wetlands restoration; wetlands hydrology; modelling; ecosystem protection; flooding terrace

1. Introduction

Wetland habitats and their unique vegetation have been subject to many threats all over the world, mainly related with different drainage practices [1]. In western Europe, in particular on large wetland areas, drainage-irrigation systems were installed to transform them into productive grasslands or meadows, as well as for other specific goals like flood protection [2–4]. For many decades without proper water management on those areas, hydrologic conditions have been substantially changed, leading to gradual loss of valuable ecosystems [1]. It used to be a frequent case, that the parameters of water management systems (i.e., discharge or drainage rates, water damming heights) were not properly adjusted and did not maintain water tables necessary for native wetland vegetation [3]. Fortunately, some wetland areas, like the Southern Całowanie Peatland near Warsaw, Poland have been reported to maintain valuable flora species, most likely as a result of drainage rates decrease since the hydrologic system has been allowed to revert to more natural state [5,6]. On sandy soils prevailing there, we found *Caricetum gracilis* stands (*Carex* shrubs) which promotes that area to a high rank from the viewpoint of nature conservation [5,7,8]. Since those stands have still been well preserved, there arose contemporary management dilemmas—whether (and how) to reintroduce the control of water levels, striving at the restoration of plant communities, or to leave the system as directly uncontrolled. Undoubtedly, the future of many wetland territories—especially in Poland—will be affected by decisions made by liable authorities, which require evidence for the feasibility of restoration process [9]. The decision-making ought to be based on hydrological criteria that can be incorporated into modelling studies and enables one to compare different management scenarios. One of the biggest uncertainties in the restoration of wetland hydrology is the form of the criteria, and the environmental variables that can be easily attributed to target habitat quality—i.e., water levels or flooding frequency [6,10]. Since the relevance of criteria is still subject to discussion, we considered the adoption of threshold values of ground water levels for sandy soils on the basis of Polish experience, summarized by Szuniewicz [11] as: minimum allowable depth (upper limit): 0.35 m, mean depth: 0.40 m, and maximum allowable depth: 0.45 m. Those values are extensively used over the area of Poland, being justified by research on a wide range of soils. In this way, we attempted to ensure the reliability of the analyses herein, basing them on values firmly related to soil physical properties [7,12].

Taking the results of two surveys that discovered vulnerable, river valley habitats on shallow water table soils into account, we aimed to apply ground water modeling and to determine proper criteria to prove the potential for hydrologic restoration of the Southern Całowanie Peatland. It was assumed that by increasing water levels in the existing network of channels, ground water table position would meet threshold values for the maintenance of *Carex* stands within a sandy-valley terrace.

2. Material and Methods

2.1. Research Area

The selected research area of 588.8 ha is the Southern Całowanie Peatland, which has already been under protection as a habitat for endangered wetland species of flora and fauna for about 10 years. It is located 35 km south of the capital city of Warsaw, and constitutes only part of a large wetland complex that covers a wide extent of the Valley of the Vistula River. The whole Całowanie Peatland (total area of 3500 ha) forms a vast and interrelated system (Figure 1), containing valuable landscape components such as raised and transitional bogs and single-swath meadows—the biodiversity of which strongly depends on human maintenance and which have been claimed to be one of the most vulnerable habitat mosaics in Europe [5,7].

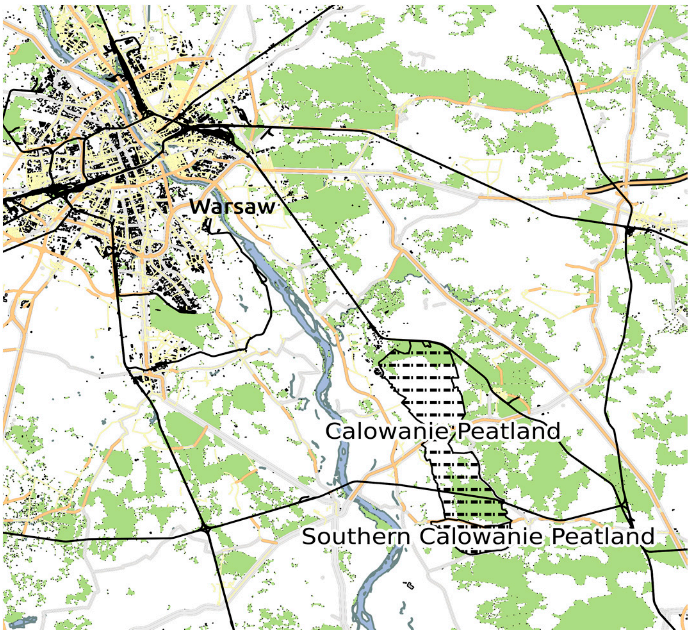

Figure 1. Location of Całowanie Peatland Protected Area, Poland. The Southern part was considered to be the research area.

The central and northern part of the Całowanie Peatland have already been subject to a wide range of research; however, the southern portion lacked sufficient attention until 2011, when urgent management issues arose [5,7]. It is surrounded by agricultural lands, but the development of new recreational areas will most likely affect existing hydrologic conditions. Hence, it is crucial to stress protection goals and give a thorough consideration to its possible future status, function, and use.

2.2. Geological Setting

Southern Całowanie Peatland is situated in the glacial valley of the Vistula River (the largest of the Polish rivers), within the boundaries of its flooding terrace, and partly at the edge of the lower non-flooding terrace. It is a quaternary ice-shaped plateau bounded by uplands 6 km to the east and the Vistula River 3.5 km to the west [5]. Local altitude differences are negligible, except for the ice-formed upland moraines, having considerable slopes. Mean altitude at the study site equals about 95 m above the mean Baltic sea level, with exceptionally few deviations exceeding 0.5 m. Geological survey showed prevailing sandy deposits in the valley, of a mean thickness equal to 10 m, underlain by silty loams (Figure 2). Regional, unconfined aquifer is built of the sand and silty loams stand for its impermeable base. Recharge to the aquifer is in the form of lateral inflow from the uplands and rainfall infiltration, enhanced by a lack of low permeability units (aquitards) that would also hinder potential contaminant transport. Ground water discharges to the Vistula River (the regional drainage base), and in some local-valley wetlands. Phreatic water tables are found at depths ranging from 1 to 5 m, and their position close to the surface of the land would contribute to wetlands formation [5,7]. Estimates of aquifer horizontal and vertical conductivity showed its homogenous character and values ranging from 16 to 30 m/day [5]. Materials observed in 20 soil borings of a depth up to 7 m, taken across the site, proved the presence of sandy deposits. Laboratory tests proved that they were very homogenous and contained from 88% to 94% sand fraction, from 0% to 3% loam, and 1% to 6% of silt, and the hydraulic conductivity derived from granular data reaching from 24 to 30 m/day [10,13]. Ground water levels were observed at six double-piezometer locations, with one tube screened to the depth of 2 m and the deeper one at 7.5 m below ground, finding no head difference between them. A distinctive feature was also a relatively large organic matter content of the soil at depths from 0 to 0.3 m, amounting to 15%, with the minimum value of 3%.

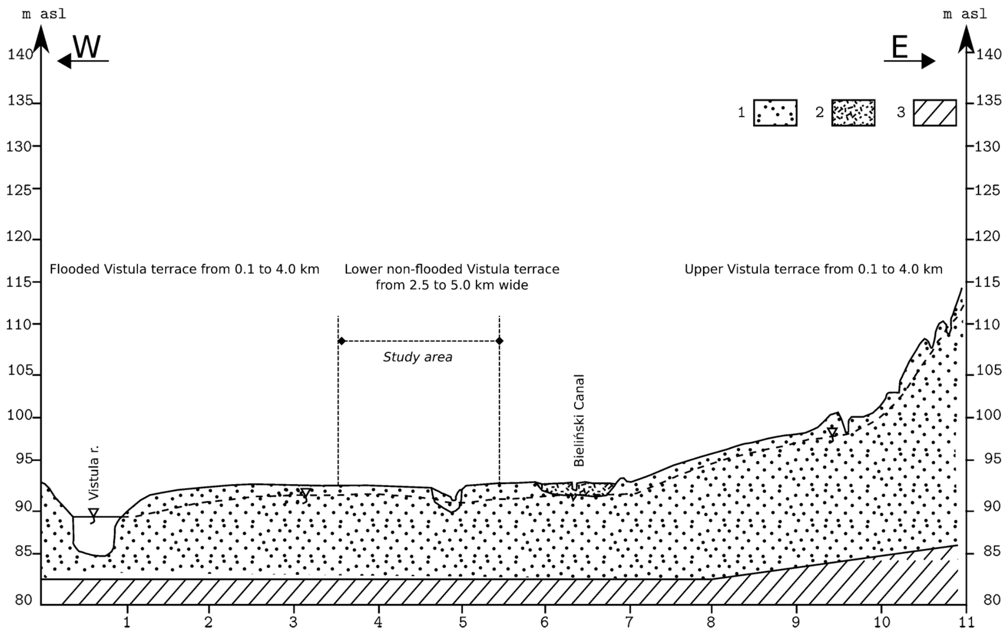

Figure 2. Geological cross-section of the Vistula Valley and the study site, where 1 stands for sand, 2—peat and riverine silt, 3—silty loam.

Plant communities were monitored over the study site in years 2003–2004 [5], and also in 2011. Among those dominating over the area, *Caricetum gracilis* (*Carex*) shrubs were found with a considerable share of *Glyceria maxima*, *Rorippa amphibia*, and *Iris pseudacorus*. Particular habitat conditions for the above-mentioned species involve river valleys and shallow lake basins with the dominance of mineral-organic deposits, and ground water levels near land surface [14]. Nearly permanent flooding is their permanent feature; thus, they are often named riverside carrs. On the other hand, numerous *Molinia* meadows appeared within the study site, attributable to peat-mineral or marsh soils, characterized by variable water content and ground water depth of 0 to 1.5 m, which makes them permanently or periodically wet or moist [8,14,15].

2.3. Channel Network

The study site is part of a large drainage-irrigation system constructed in the valley of the Vistula River in order to develop proper soil water content of existing peatlands and arable lands (Figure 3) [7]. Another important goal was to provide for flood hazard mitigation in that valley. Like many similar systems in Western Europe, that system was not sufficiently managed throughout decades, and thus failed to realize its designed functions [3,7]. However, the presence of wetland plant species suggests that the current function of the system should be to increase ground water levels in areas targeted for restoration.

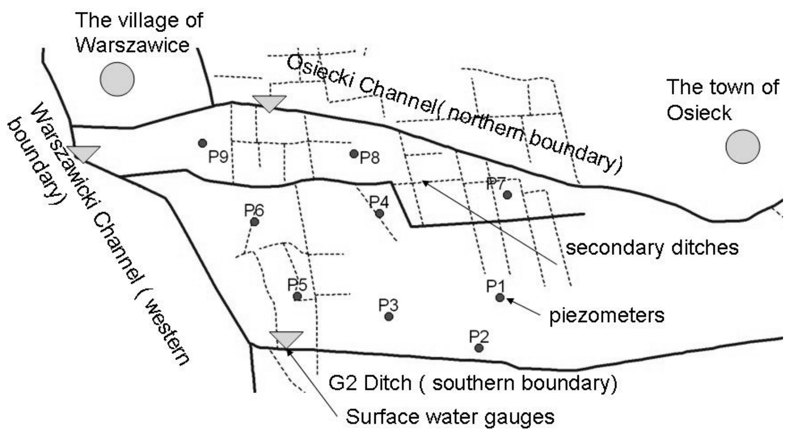

Figure 3. Hydrographic network of the Southern Całowanie Peatland.

The study site is bounded from the north, south, and west by main drainage irrigation channels, which served in the past to supply water to secondary ditches within the area [7]. Those ditches have had limited maintenance, and were finally overgrown with vegetation. The present physical condition of the system enables the surface water levels to be adjusted only in the main surrounding channels.

2.4. Ground Water Model

In order to conduct analysis of ground water table changes versus the assumed canal water levels, we utilized the common and recognized Modflow code, which can simulate ground water flow response to changing boundary conditions. The governing partial-differential equation of this model can be written in the following form [16]:

$$\frac{d}{dx}\left(T_x\frac{dH}{dx}\right)+\frac{d}{dy}\left(T_y\frac{dH}{dy}\right)+\frac{d}{dz}\left(T_y\frac{dH}{dz}\right)-W=S\frac{dH}{dt} \quad (1)$$

where T_x, T_y, T_z—aquifer transmissivities in three directions: x, y, z (m^2/s); H—hydraulic head (m); W—inflow or outflow from internal sources or sinks of water (m/s) (e.g., rainfall, evaporation, channel seepage); S—specific yield (dimensionless); t—time (days, years, etc.).

Ground water flow in a sandy aquifer was modelled in this study, which was deduced from available recognition of hydrogeological conditions. Since grain composition tests and water level measurements at different depths proved no heterogeneity in the aquifer system, it was possible to use one numerical layer of Modflow code to perform the simulations. Because only part of the aquifer was modelled, first type boundary condition was applied to the channels existing from the northern, western, and southern directions, while from the east, the aquifer recharge flux was imposed as second type boundary condition. The impermeable layer of silty loams underlying the aquifer was treated as a no-flow boundary.

2.5. Model Calibration

A calibration process was performed using a trial and error procedure in order to estimate such values of aquifer conductivity and eastern inflow rate for which a reasonable match between modeled and observed ground water levels was achieved. Ground water levels used for calibration were measured in the network of piezometers in 2012, and surface water levels in channels were gauged in that year as well. Moreover, they were expressed in meters above the mean Baltic sea level datum. Based on geological surveys, reasonable assumed values of hydraulic conductivity of the aquifer varied from 16 to 30 m/day, while the ground water inflow rate applied on the eastern boundary ranged from 0.5 to 2.1 m^3/day/m [5]. Both parameters were changed individually, followed by a visual comparison of observed and modeled piezometer heads (Figure 4), correlation coefficient, and standard deviation. The conductivity and inflow values were finally considered as acceptable when standard deviation reached 0.3 m and correlation coefficient was equal to 0.82. As a consequence of the calibration procedure, aquifer conductivity was set as 25 m/day and eastern flux equal to 1.7 m^3/day/m.

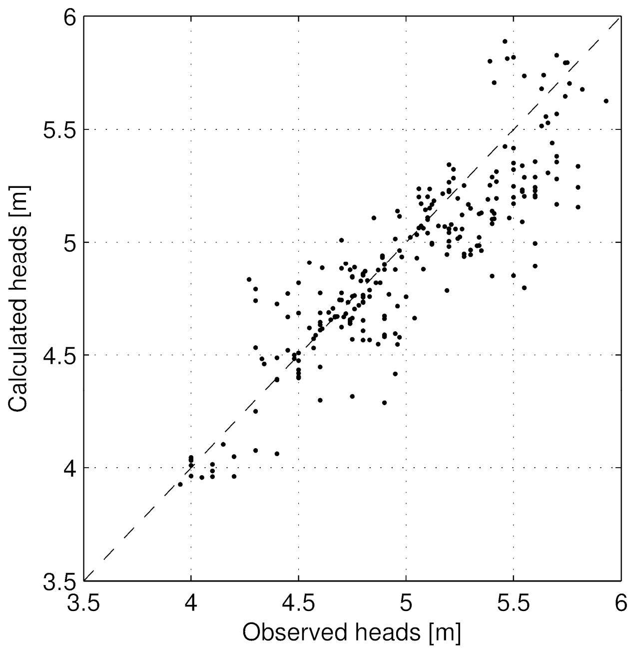

Figure 4. Scatter diagram for modeled and observed ground water heads with linear correlation coeffieicent equal to 0.82. The heads are related to local model datum, where "0" stands for 90 m above mean Baltic sea level.

The upper boundary condition (recharge flux through the surface into ground water system) could be treated in the Modflow software (Processing Modflow-version 5.3.1. Copyright © 1991–2001 W.H. Chiang and W. Kinzelbach) as P-E—that is, precipitation rate minus evapotranspiration. Precipitation totals were achieved by linear interpolation over a wider area on the basis of the records from three stations: Warszawa (37 km), Siedlce (about 40 km), and Kozienice (about 37 km). However, only meteorological data from Kozienice were used to calculate potential evapotranspiration according to Penman–Monteith method [10], since that station largely reflects the conditions outside the city area. It should be stressed that those values are not fully representative for the Całowanie Peatland, and should also undergo calibration. Nevertheless, it was omitted in the present study so as to keep the calibration procedure as simple as possible. On the basis of the ground water measurement availability, it was decided to run the model with a decade time step; hence, the input fluxes of precipitation and evapotranspiration were calculated as decade totals.

In this study, it was decided that only the most uncertain parameters will undergo calibration (hydraulic conductivity of the aquifer and inflow from east). The input from precipitation and evaporation could also have been subject to adjustments, as they come from interpolation for a wider area, being influenced by spatial variability of hydrometeorological processes. Additionally, for further simulations, the calibrated inflow from the east remained constant, which most likely influenced model output. However, it was justified by the fact that no water level observations existed from that direction, which would provide more accurate data for applying boundary conditions.

2.6. Model Validation and Exploitation

Next, the model was validated on the basis of ground water levels measured throughout 2013. In the simplest manner, we estimated the quality of the model by visual comparisons (Figure 5) and also by calculating correlation coefficients between modeled and observed water tables for all piezometers. The achieved values (0.6–0.79) do not indicate good or very good quality, but rather suggest a satisfactory (or acceptable) one.

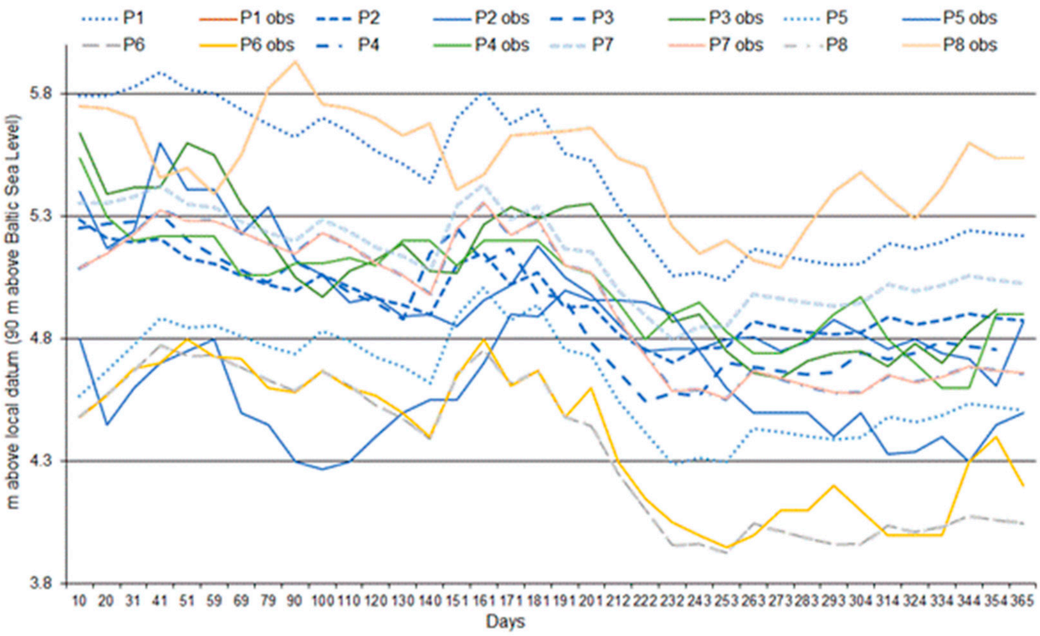

Figure 5. Comparison of the observed and modeled water tables for 2013. Each color pertains to an individual piezometer.

After the validation, the model was used to calculate ground water heads for the assumed channel water levels, so as to estimate potential impact on *Carex*-dominated sandy wetland and find relevance to restoration goals. We found it to be a practice in restoration projects to make use of modelled ground water head distributions for scenario comparisons and estimation of different management practices. Here, the first scenario assumed actual water levels in the main channels, and the second one involved raising the levels by 0.5 m to find out if such hydrological remediation helps to keep predefined ground water tables on a site undergoing restoration.

3. Results and Discussion

On the basis of data collected for 2014, the simulation of ground water levels for the current status of the system was performed with the use of the validated Modflow model. As it was already mentioned, the input values for that year involved precipitation and evapotranspiration fluxes, ground water inflow from the eastern direction, and measured water levels in the main ditches, which were maintained by the existing hydraulic structures. The physical condition of those structures (as it was stressed before) is a vital issue for the analysed area, with respect to water management and the maintenance of environmental status. On the basis of the existing assessment of the structures [5,7], it was found that an allowable rise in channel water table is equal to 0.5 m, which was considered in the second scenario.

Ground water levels, modeled with decade time step, were averaged for 2014 (Figure 6) and subtracted from terrain elevation (Figure 7). In this manner, mean ground water depths were determined. In the first scenario, which reflected the current status of the system, mean ground water depth varied from 0.3 to 0.9 m in the middle of the area, and near the canals it ranged from 0.9 to 2.4 m. We found that the calculated depth followed patterns typical for areas surrounded by drainage-irrigation channels. Maximum depth values were noted close to channels, while in the middle of the area, near piezometers P4, P5, and P6, they approached land surface elevation.

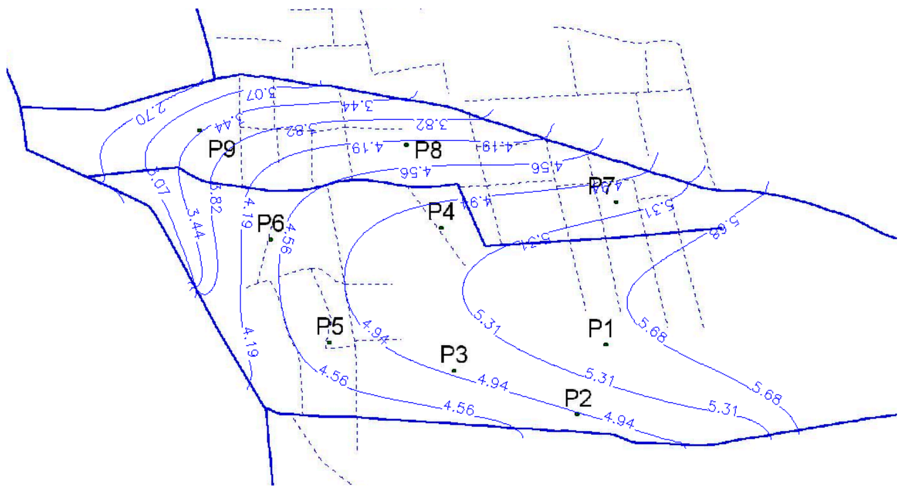

Figure 6. Mean ground water heads for 2014 related to local model datum, where "0" stands for 90 m above mean Baltic sea level.

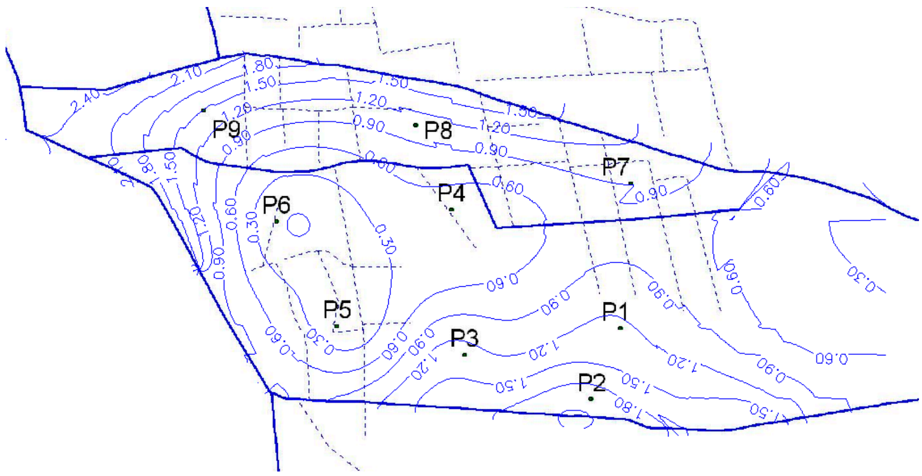

Figure 7. Mean ground water depths for 2014.

In the second scenario, which involved a 0.5 m rise in channel water levels, the possible increase in overall ground water table approached 0.3 m, except for the vicinity of ditches, where it ranged from 0.4 to 0.6 m (Figure 8). It was initially guessed that it would not be feasible to sufficiently increase water tables in a close-to-ditch zone; however, the whole analysed area was indeed subject to change in ground water table as a result of altered ditch levels.

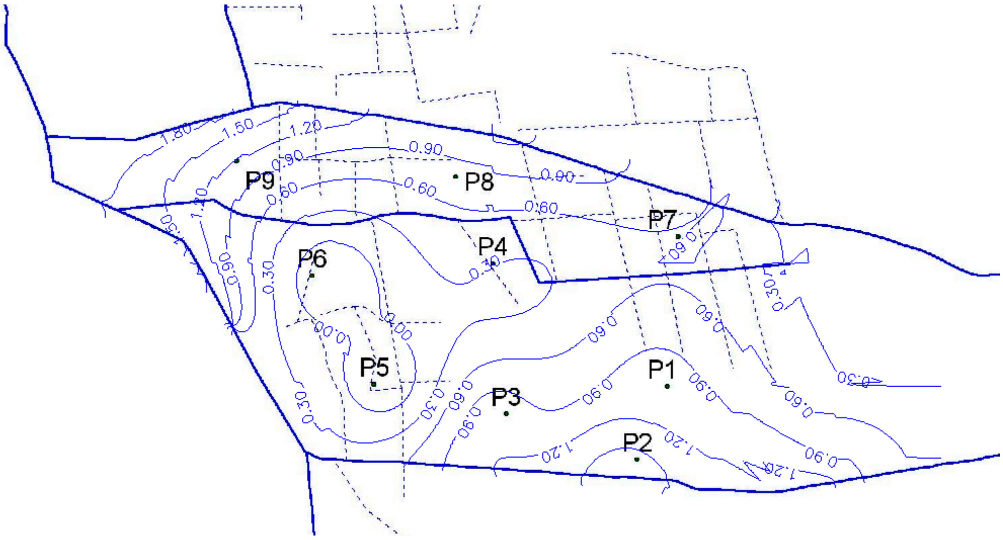

Figure 8. Mean ground water depths in scenario 2—water levels in ditches raised by 0.5 m.

Next, the calculated ground water depths were utilized to determine the potential area of restored wetland. For this purpose, previously adopted threshold values were imposed on modelled depths for both scenarios. If the mean water table was found to be between the assumed upper and lower limit (0.35 to 0.45 m), we claimed the restoration target to be reached. In the current status of the system, only about 16% of the area (92.6 ha) was found to maintain the predefined ground water table range. In the second scenario (channel water tables raised by 0.5), that area extends to 29% (171.6 ha). On these surfaces, we can expect more favorable initial conditions for the maintenance of vulnerable *Carex* or *Molinia* habitats underlain by sandy soils within a flooding terrace. The remaining part (71% of the area) would be still subject to lower water table and insufficient capillary rise in the soil, not reaching the root zone. We wish to emphasize that the above-mentioned findings should be treated as relative, because they are directly dependent on the adopted criteria. Having assumed other allowable limits of hydrologic characteristics, we might achieve a different view on the conservation of wetlands versus the obtained water levels. The appropriateness of hydrological criteria for the assessment of wetland restoration has already been discussed in scientific literature [6,12] considering mean water levels and its extremes (threshold values), as well as other hydrological characteristics (e.g., flooding frequency is mainly based on expert knowledge, resulting mostly from observations of reference ecosystems) [8]. Within those ecosystems, we find such water level dynamics that the existing habitat conditions (soil properties and plant communities first of all) are preserved well and can be treated as patterns for nature conservation. At present, empirical attempts were made to relate ground water levels with certain habitat quality or type or to find optimum hydrographs for particular plant groups within an ecosystem [8]. This still seems to be subject to discussion, because for hydrologic aspects, the water levels and resultant soil water content are the most important parameters; however, other ecological issues also need to be addressed; i.e., the seed bank, light availability, nutrient cycling, etc. This may lead to more interdisciplinary eco-hydrological approaches. As of yet, the formulation of particular criteria tends to be questionable, and one has to decide which environmental qualities could be assigned to particular moisture ranges. The soil water management approach we decided to present helps to maintain water levels for sandy soil types, which secure 8% oxygen content in the root zone as an effect of capillary rise in the soil. It is then transparent from the soil point of view, and directly related to its basic physical properties, but again may not be sufficient for other ecohydrological issues.

4. Conclusions

Results of hydrogeological surveys along with the recognition of dominating plant species within the Southern Całowanie Peatland revealed the need for a wise use of the existing drainage network. *Carex* and *Molinia* stands were still preserved on a sandy flooding terrace, especially where ground water tables would not fall 1.5 m below the land surface. This corresponds with the results of ground water modeling for the current status of the hydrological system. Another feature that is consistent with the depicted geological setting is a high organic matter content of the topsoil. All of the above findings undoubtedly suggest that there are perquisites for swamp-forming processes, and the realistic restoration potential is supported by the modelled ground water table response to increased channel water levels. Having analysed the modelling results as well as the application of hydrologic criteria, we were able to form the following conclusions:

(1) Channel water level clearly exerts an influence on ground water table with a typical pattern; that is, the highest drawdown takes place close to channels, and the maximum elevation of the water table is present in the middle of the area. We try to describe that influence as conductivity-dependent, because its large values for existing sandy soils may cause high exchange between canals and ground water horizons, undoubtedly contributing to the preservation of the natural values of a flooding terrace.

(2) Depth to water table was analysed according to the adopted criteria, which describe sandy soil wetness due to effective capillary rise. According to that criteria, maximum allowable depth to water table may not be higher than 0.45 m, the mean depth should be equal to 0.40 m, and the minimum reaching 0.5 m. The assumed threshold values of ground water table (0.3 to 0.45 m below land surface) were achieved on maximum 29% of the area if the channel water levels were increased by 0.5 m in the second analysed scenario. The first scenario (which reflected the actual status of the system) guarantees proper water levels only on 16% of the area. We wish to stress that the restoration target was achieved when ground water table position was between the adopted extremes. This was indeed an assumption. First of all, the criteria seem to be relative, and we also claim that the prescribed water level range is directly assumed as a permanent feature of well-preserved habitats (and their plant species composition), and may be used for scenario comparisons in hydrologic and water management analyses. The appropriateness of the applied threshold values results from their extensive use over the area of Poland and firm relation to crucial soil properties.

(3) Hydrologic conditions on sandy terrace favorable for dominating *Carex* species and widespread *Molinia* meadows were possible in the middle of the area. As shown by the modelling results, they were not achieved in close-to-channel zones, which would require other hydrologic remediation.

(4) Adaptive channel water management is no doubt an option for the maintenance of habitats on sandy deposits of flat river valleys. More detailed scenario studies are indispensable for the decision making on the extent of restoration area.

Author Contributions: The study was completed with cooperation between all authors. Andrzej Brandyk conceived and designed the experiments, prepared the conceptual model and wrote material and methods as well as discussion. Grzegorz Majewski performed field measurements, and Adam Kiczko prepared the figures, modeling data and part of the results. Andrzej Boczoń and Michał Wróbel took part in fieldwork and results discussion, Paola Porretta-Tomaszewska elaborated the conclusions.

Conflicts of Interest: The authors declare no conflict of interest.

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