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A GIS Multi-Criteria Analysis Tool for a Low-Cost, Preliminary Evaluation of Wetland Effectiveness for Nutrient Buffering at Watershed Scale: The Case Study of Grand River, Ontario, Canada

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Abstract: One significant concern of Ontario's water quality management is the reduction in nutrient export. Decision makers have considered nature-based solutions, such as wetlands, depending on their cost-effectiveness for nutrient filtering. All wetland ecosystems interact with the surrounding environment; however, their performances are not always known, which prevents a fair comparison with other treatment alternatives. This study presents a methodological approach for mapping areas that can potentially support effective (or ineffective) wetlands for nutrient buffering. The Grand River watershed, Ontario was selected to demonstrate the methodology. Geographic Information Systems (GIS) are combined with multi-criteria analysis (MCA) to evaluate wetland effectiveness under geomorphological, climatological, hydrological, and land use factors. The selected factor maps (criteria) are normalized, and then used as inputs in an analytical hierarchy process (AHP) and weighted by experts based on how these factors affect wetlands' performance. The promising areas' spatial distributions are the output, which is compared with previous studies' mappings of nutrient concentrations in the watershed. The proposed tool provides a low-cost preliminary estimation that informs policymakers if wetland solutions could achieve the desired environmental goals. This methodological approach supports Canadian wetland conservation efforts and enables a more complete decision-making process.

Keywords: multi-criteria analysis tool; water quality; wetland effectiveness; phosphorus; Grand River watershed; Ontario Canada

1. Introduction

Deteriorating water quality is one of Canada's main water resource management issues, especially in Ontario. Lake Erie's eutrophication and the accompanying economic consequences have led to phosphorous reduction oriented environmental policy, considering a plethora of measures and practices [1,2]. These measures basically include wastewater treatment plants, land use changes, environmentally friendly agricultural practices, and nature-based solutions (wetlands, buffering zones, etc.). The nature-based solutions (and mainly wetlands) are a significant environmental component, providing multiple ecosystem services (ES) (e.g., stormwater retention, nutrient filtering, climate stability, flora and fauna, soil improvement, etc.) [3]. One of the causes of increased nutrient runoff is the conversion of wetland areas into (more profitable) farmland [4]. Subsequently, the importance of wetland preservation and restoration has been increasingly highlighted by provincial



and federal governments in the last decades [1]. However, wetland areas have continued to be lost, while more wastewater treatment plants have been built, but without tackling non-point farming pollution [1,2].

Although practices for improving surface water quality are more or less known, it is difficult to have the same basis of comparison with equal certainty with respect to the implementation of the most appropriate practices. More specifically, a wastewater plant's performance can be known from a design study (e.g., x% reduction in phosphorous loads), but this is not the case for wetlands. A wetland's performance for nutrient filtering depends on various factors (physical, geomorphological, hydrological, climatological, vegetation, soil, surrounding land uses, inflows, initial concentrations, connectivity with other water bodies, groundwater recharge, etc.) [5]. Therefore, an interdisciplinary and case-specific study is required to give policymakers a proxy of a wetland's performance. This process is very rarely followed because it is time-consuming, costly, and it demands specialized knowledge. This is justified by the fact that there is a lack of such studies in Canadian literature [5].

At this point, our research question is, "Is it possible to provide a low-cost, fast, preliminary estimation of wetland performances, covering most of the factors that determine it, in order to provide policymakers with more info on such solutions?" To answer this question, we propose a novel approach, based on the following classic techniques: Geographic Information Systems (GIS) are used to map the factors that affect wetland effectiveness, combined with multi-criteria analysis (MCA) (to assign weights to these factors), and produce a map with classified wetland potential performances. This has been a challenging task worldwide, tied with computational challenges and uncertainties, as the different factors (data) and the ways they interact are a complex dynamic system, which cannot be validated [6]. The attempt to map the result of the complex process of nutrient filtering by wetlands is a novel element, valuable for water quality management. The use of classic techniques makes the tool easily replicable for analysts, however, not necessarily academics. The sentence should be: The methodology is demonstrated at the Grand River watershed, Ontario, that directly runoffs to Lake Erie. The watershed scale of the analysis facilitates the extent of data usage, covers the broader ecosystem in which wetlands are a function, makes their interaction more comprehensive, and is in line with nutrient reduction goals that refer to the outlet of the watershed.

The integration of MCA into GIS applications has been demonstrated for eco-environmental quality, vulnerability, and pollution [7–15]; however, to our knowledge (and after a comprehensive literature review), this is the first application in Canada, and the first timed it has been implemented for a spatial evaluation of wetland effectiveness. Knowing each solution's performance is essential when select a policy strategy, rather than just following traditional (but not always adequate) least-cost approaches. Thus, the proposed framework is an important step towards the following: (a) achieving a more complete decision-making process, (b) supporting Canadian wetland conservation efforts, through providing insights on a more efficient wetland-farmland allocation policy based on its estimation results, (c) filling this wetland-related knowledge gap, and (d) encouraging more studies on wetlands' potential to reduce nutrient concentrations in Canada.

2. Study Area

The Grand River watershed in southwestern Ontario is an area of 6800 km². Grand River and its tributaries flow into Lake Erie. The watershed's climate is moderate to cool temperate, with four seasons, characterized by rainy-snowy winters and hot-humid summers. There are various geological schemes in the area that create different hydrologic conditions. The northern part, which consists of till plains, and the Haldimand Clay Plain in the southern part create high surface runoff and limited infiltration [16]. On the contrary, the watershed's central part consists of moraines and sand/gravel remnants of glaciers that facilitate infiltration while surface runoff is low [17]. The topography is mainly flat (Figure 1A) and with pervious soils. The main soil types in the watershed are Perth (9.4%), Huron (7.8%), Guelph (5.9%), Burford (4.1%), and Brantford (4.1%) [17]. According to the digital elevation model (DEM) [18], the elevation ranges from +173 m (south) to +535 m (north). According to

the Canada Centre for Remote Sensing land cover data [19], the main uses include cropland (48%), grassland (21%), forest (16%), pastures (8%), urban (5%), open water surfaces (1.5%), and transportation (0.5%). The following three main reasons contribute to the increased nutrient (especially phosphorus) contamination and runoff from the Grand River watershed to Lake Erie:

- The watershed's population is approximately 1,000,000 residents, concentrated in the central region and its surroundings (i.e., the cities of Kitchener-Waterloo area, Cambridge, Guelph, and Brantford), and it is continuously growing.
- The intensification of farming activities in the rest of the watershed leads to qualitative and quantitative water resources degradation. Non-point (and point) pollution sources are the most significant challenges, especially regarding phosphorus and nitrogen concentrations [1,2].
- As shown in Figure 1B, there are still several wetland complexes, i.e., Luther Marsh covers 30 km² in the north, Horseshoe Moraine covers 50 km² of groundwater fed wetlands, Brisbane Swamp contributes to the Eramosa River in the Guelph Drumlin Field, Beverly Swamp covers 20 km² in the southeast, as well as the Keldon and Amaranth Source Areas, and Roseville Swamp [17]. However, the Grand River watershed has lost almost 70% of its historical wetlands. This percentage exceeds 85% in some areas, leaving less than 10% of wetland area, which is the threshold for a watershed to be considered "healthy" [17].



Figure 1. Grand River watershed (A) elevation map and (B) land cover map.

In this study we try to put together the data of factors affecting the potential of wetlands to treat nutrients, and develop an objective evaluation of their performance, specifically for the Grand River watershed.

3. Methodology

The proposed tool uses factors that can play a role in a wetland's ability to reduce nutrient concentrations, as criteria in an MCA model. Weights (priority values) were assigned to them, according to their importance. The result was used to produce a map (wetland effectiveness rating), given the (weighted) normalized spatial distributions of these factors' criteria. The following sections analyze these steps.

3.1. Selecting Criteria

In order to assist policymaking to consider if the path towards nature-based solutions (i.e., wetland restoration and preservation) is cost-effective, the aspects of filtering effectiveness and costs should be examined. A recent Canadian review detected more studies on associated costs than effectiveness, because of the involvement of case-specific and non-comparable factors [5]. In our previous review, only a few studies included information about these wetland-specific factors; no study mentioned or commented on all of the factors, while most studies estimated effectivenesses based on expert judgment [5]. We list all the factors used in the past to support effectiveness estimates, as well as those that made estimations difficult, made each study case specific, and prevented more general assessment, according to each study reviewed, as follows:

- Scale differences of existing Canadian studies, i.e., unit of reference of system (e.g., wetlands, watersheds, only outflows, etc.) [20,21].
- Different purposes of studies (e.g., different periods of measurements, monitoring, design, restoration, case-specific characteristics, different needs expectations from wetlands, etc.) [22].
- Different methods followed by researchers and how they estimated effectiveness (e.g., where the export was measured, seasonality, if phosphorus concentration was the main purpose or just additional estimations, etc.) [23,24].
- Specific features that define how nutrient reduction is achieved, i.e., wetland type and age of operation (or being active/inactive), average depth, length, sediment/soil type, initial concentrations, vegetation type, density and coverage, fauna, landscape, surrounding land uses, climate, hydro-meteorological factors, loading rates, etc. [25,26].

Scale is a parameter ("umbrella") that directly or indirectly affects several of the above factors. From the hydrogeological point of view, wetlands are parts of a wider ecosystem that functions in a coupled and interactive way with nature's and human's activities. Wetland-scaled studies are also necessary for specific factors, but they should be considered to be components of a broader system, the watershed, which is why wetlands' role for phosphorus contamination is examined at a watershed scale. This is also a novel element, as it addresses all the above differences. Then, the specific factors can be grouped into the following categories [5,27,28]:

Land use criteria A wetland's surrounding land uses majorly affect its performance as they significantly affect its inflows' quantity and quality;

Soil and vegetation criteria Soil type, vegetation type and density result in different nutrient-absorbing capacities;

Climatic criteria Temperature, precipitation, sunny hours, ice coverage, etc. are meteorological factors that affect the speed of the processes and the response of other factors (such as soil and vegetation), which absorb part of nutrients, contributing to the overall performance of a wetland;

Landscape/topography criteria DEM-related parameters which allow the calculation of slope, aspect, topographic position index (TPI), topographic wetness index (TWI), overland flow distance, etc. are factors that show the water concentration inside the watershed, topographic features, and are important elements to consider for wetlands acting as sources or sinks of nutrients, and flow rates and accumulation (or the time that phosphorus stay in the wetland) can also be indirectly addressed.

Spatial data (raster files) were sought for the above parameters. Of course, a wetland's ability to filter nutrients is a multifactorial context and more criteria can be used to describe it (e.g., vegetation, wetland type, etc.) [29]. However, from the available data, we used the following representative criteria for each category: land Cover spatial data for land uses, soil type for soil, temperature for climatic, slope, and TPI and TWI for landscape and topography criteria. This set of criteria has the following advantages (i) the criteria have a small number which makes the computational process simpler, (ii) a double effect is avoided during the evaluation process since the criteria stand for different drivers, and (iii) all criteria are in agreement with other studies (see next section for each case) that highlight

the main drivers of the nutrient-filtering process from natural or constructed wetlands [30–32]. In the following subsections, we present the meaning and role of each selected representative criterion that was used in this study.

3.2. Data Preparation: Criteria Scores and Normalization

Before forming the MCA model, the above criteria (the spatial data collected) need to be converted to the same "units", and scale, i.e., a coherent scoring in a low–high system, indicative of their influence on nutrient filtering ability. This process is described below for each criterion.

The relevant data were obtained from official sources [18,19,33–35]. Typical techniques were used to calculate slope based on the 5 m resampled (natural neighbors) DEM. Higher effectiveness was assigned to higher slopes, as they are indicative of water accumulation and flow in the central part of the watershed [36].

Regarding the land use mapping, the classification in Figure 1B was used. The only layer that needed to be added was the detailed distribution of the watershed's wetlands, in order to have a clearer picture. This dataset was obtained from the Ontario Ministry of Natural Resources and Forestry [35]. A detailed land cover map was essential, as land use majorly defines the phosphorus (P) and nitrogen (N) exports (kg/ha/y). According to the P and N exports per land use, the scoring was assigned from less effective (0) to more effective (1) as follows: cropland, grassland, broadleaf/mixed/needleleaf forests, urban and built-up areas, shrubland, water and wetlands, and barren lands [37,38].

The Ontario Detailed Soil Survey [39] dataset series consists of georeferenced soil polygons with linkages to attribute data, for example, soil name file (SNF) and soil layer file (SLF). Together, these datasets describe the spatial distribution of soils and associated landscapes for nearly all agricultural areas in southern Ontario. Soil types, as used for the present work's purposes, address the ground's drainage and perviousness; pervious soils have the ability to remove higher quantity of nutrients, as they allow infiltration, thus the scoring "low" refers to poorly drained soils and "high" effectiveness to rapidly drained soils [40].

Temperature (T) is not uniformly distributed in the watershed and this is an element that can affect the processing of P and N by wetlands. A temperature-gradient approach was followed based on the DEM and the broader area's stations' meteorological data, which provided T's spatial distribution in the watershed. For the temperature gradient, four stations of the watershed were used for the period 2012–2019. Low temperatures slow down nutrient absorption processes by wetlands, while higher temperatures support higher effectiveness [6,41–43].

Topography and wetness indirectly address precipitation and are parameters worth examining for wetland efficiency, because they increase the precision of the results [44,45]. TPI and TWI were also calculated based on the DEM, using the same resolution. TPI expresses relative locations of interest (e.g., the topographic position of a location may be hilltops, plains, exposed ridges, or other features). TWI (SAGA (System for Automated Geoscientific Analyses) wetness index [46]) is a physical attribute of water accumulation areas, as it accounts for the hydrographic position of the watershed's grid cell, the drainage area per unit contour length, and the presence or absence of flat lands. Thus, a proportional relation was followed for TPI effectiveness and an inversely proportional for TWI effectiveness [47].

After converting the criteria in this scored-based low-high scale, it was necessary to use the same units for the application of the multi-criteria weightings [48]. This was achieved by normalizing each of the criteria in a 0–1 scale using the min-max normalization technique. Figure 2 shows the six selected criteria and their normalized spatial distribution used for the detection of potential wetland effective areas.



Figure 2. Normalized spatial distributions of the selected criteria. Low refers to less effective and high to more effective filtering potential, based on each criterion's features. The selected criteria. (A) Land use; (B) Soil type; (C) Temperature; (D) Topographic wetness index (TWI); (E) Topographic position index (TPI); (F) Slope.

3.3. Multi-Criteria Analysis (MCA) Model

For the evaluation of the above criteria, an MCA model was formed using the analytical hierarchy process (AHP). The AHP assigns and distributes weights of significance to the defined criteria (through pairwise comparisons), creates hierarchical structures to develop priorities (based on the judgment of the user), and then classifies (ranks) the solutions [49–51]. The AHP was chosen for this problem because it facilitated the organization and formation of the problems, it performed well with 5–10 criteria, it allowed us to control each step of the process, and it produced a set of weights linked to the various criteria/objectives [52–54].

The ranking was accomplished with binary comparisons based on experts' judgment regarding which criterion was more important for wetland effectiveness. A specific comparison between two criteria was characterized as "equal", "marginally strong", "very strong", and "extremely strong" [55,56]. The degree of randomness of the answers was expressed by the consistency ratio (CR), which had to be smaller than 10%. For the studied problem, the weights were assigned to a 6×6 criteria matrix (for a single alternative, the effectiveness). The right principal eigenvector was calculated for the comparison matrix. Subsequently, the synthesis of these preferences was carried out to determine which criterion had the higher priority and effect on the estimated result [53]. Through the comparison relations, the criteria were weighted (a_{ij}) for each map, as shown in Figure 2 (weights for each one of the six criteria, w_i), and a spatial value occurred for each grid's cell, i.e., the potential effectiveness (*i*):

$$A_{AHP}^{i} = \sum_{j=1}^{6} \mathbf{a}_{ij} \times w_j \tag{1}$$

Subsequently, the result was a map of low-high potential effective areas (as the total of the 5 m grid cells , A^i_{AHP}). Finally, the sum product of Equation (1) and Boolean algebra through GIS were used to produce the final map with areas that could support effective wetlands for nutrient filtering.

4. Results

The AHP 6 × 6 criteria-weighting matrix was formed and completed by the authors, for the purpose of the tool's demonstration of "by expert user", which is often used for similar AHP-GIS applications [48,57–61], where experts' opinions tend to converge anyway [48]. Table 1 shows an example of the scale used for the evaluation, where each criterion gets a comparative score to the other criteria. The procedure described above was followed, the results were normalized and examined with the consistency ratio (CR) approach, which was acceptable (<10%). Table 2 presents the final priority vector with the weights assigned to each criterion, the resulted RI and CR. The weightings consider each variable's impacts on phosphorus reduction and their interactions, scale, effect range, actual significance in the examined watershed, and are according to the cited literature.

Table 1. Example of the analytical hierarchy process (AHP) pairwise comparison using the Saaty scale.

	Temperature	TWI	TPI	Slope	Soil Type	Land Uses
Temperature	1	2	1/6	3	1/6	1/7
TWI	1/2	1	1/7	1	1/7	1/8
TPI	6	7	1	7	1/2	1/3
Slope	1/3	1	1/7	1	1/8	1/9
Soil type	6	7	2	8	1	1/3
Land uses	7	8	3	9	3	1

Table 2. Relative weights of the criteria, randomness index (RI), and consistency ratio (CR), resulting from the AHP.

Priority Vector					Randomness Index (RI)	Consistency Ratio (CR)		
Criteria	Temperature	TWI	TPI	Slope	Soil Type	Land Uses	Criteria n = 6	CR = 7.72%
Weights	0.06	0.03	0.20	0.03	0.25	0.42	RI = 1.24	

The results were classified using Natural Breaks (Jenks), a typical and most used GIS classifications technique [62–64]. It was preferred because of its ability to reduce the variance within classes and maximize the variance between classes, providing the optimum arrangement of values into separate classes that could be displayed on a choropleth map [65]. The classification follows the ranking of three classes, i.e., low (1), moderate (2), high (3) (Figure 3).

The north and northwest parts of the watershed have a lower concentration of wetlands, as also shown in Figure 1B. The small area that seems slightly more effective in the north can be attributed to the Luther Marsh (Figure 3). The watershed's central and southern parts resulted in the most promising areas for wetland buffer zones, in line with the existing complexes and the Grand River itself (Figure 3). Apart from the watershed's central part, the rest is dominated by farming and intensively cultivated areas, which justifies the lower ability to filter the increased phosphorus exports (Figure 1B) [66]. Of course, this is a function of the crop types, and therefore a further investigation could provide even greater detail. The southern part's high surface runoff, as well as topographic and climatic conditions resulted in a promising effective area, despite the farming activities. It is also the lower part of the watershed, and therefore filtering the accumulated phosphorus would probably have a more significant impact there. This is an interesting insight that could be useful for future consideration of alternative water quality improvement solutions. The present preliminary estimation result emphasizes areas of different features regarding wetlands and water quality improvement potential, which need different management. Concerning the managerial aspect of the results, given the higher effectiveness of the wetlands located in the central and eastern part, the need for their preservation must be highlighted. For the rural areas with wetlands of lower effectiveness potential, agricultural practices, crop replacements, and fertilizer management options are recommended. A closer study is necessary on specific wetlands, to identify if it would be better to restore or convert them into farmland.



Figure 3. Final map with areas that could support effective wetlands for nutrient filtering.

5. Discussion

The obtained results are an interpretation of the effectiveness of the watershed's wetlands in phosphorus filtering. From the beginning, this map's achievement with an easy, holistic, and low-cost method was a very challenging task, with limited to no previous experience to build on, especially related to natural wetlands [67]. Subsequently, validation of the results was also difficult, for several reasons which included the following: It required integrated knowledge and understanding of the problem as well as integrated data (often difficult to collect); there were no similar applications or even monitoring at a watershed's scale; the examined processes were complex and dynamic; and the wetlands' ability to filter nutrients was dynamic and case specific, with different methods used in the literature to estimate it, with different measurement, application, or computational scales. However, we attempted to verify the results by comparing our output with a previous study that provided P and N exports for the Grand River watershed. P and N export distributions were very similar in the watershed, and since P was the main focus and issue in the broader area and in our study, it was used for this indicative verification. Figure 4 compares the (digitized) respective map produced recently by [16] and the map shown in Figure 3.



Figure 4. (**A**) Phosphorus (P) actual concentrations in the watershed; (**B**) Areas that could support effective wetlands for nutrient filtering (black dots represent common areas within the red classes of (**A**,**B**)).

In Figure 4A, we recreated the map produced by [16] (digitized and with assigned value classes of P export per polygon), to facilitate the visual comparison of the results. Both maps are normalized and classified in three classes, indicating low, moderate, and high P exports and effectiveness, respectively. The verification can only be considered indirectly, i.e., low P exports can indicate effective wetland potential in the watershed, and vice versa [68]. A validation process will not be the case here, as several factors distinguish the two maps' outputs. P exports are often based on land use, while several additional factors affect wetlands' treatment ability. In addition, the wetlands that may have contributed to the map in Figure 4A are the existing ones, while the map in Figure 4B examines their potential effectiveness throughout the entire watershed.

According to the results produced in Figure 4B, the watershed's biggest area is in line with the map in Figure 4A. Other studies in the Grand River watershed have also resulted in similar spatial distributions of P and P-sediment exports that support our findings [66,69,70]. The central and west areas are quite similar, while slight differences appear in the northern and southern areas. This is reasonable because of the following: (a) There are differences because of intensive loads, especially for the intensively cultivated north and south parts of the watershed. The increased exports are difficult to be completely filtered by the wetlands. (b) The river's flow affects the southern drainage point's values. (c) The two maps, therefore, are used for an indirect validation (not completely homogenous, just indicative), as mentioned before. Despite the different purposes of the older studies and our work, the comparison provides significant elements related to the current work's results. The similarity among them is an encouraging sign for considering the presented results reasonable and valid.

The pinpoint locations in Figure 4B show areas where the water quality status, the actual nutrient exports, and the existing wetlands' amount and filtering ability should be examined more closely. For example, the northern part that previously had more wetland areas, indicates that the wetlands would have had the potential to filter significant amounts of P, while the existing complex is "overloaded", but still effective. The southern part of the watershed (drainage point) is also appropriate for a more detailed study in order to scrutinize the factors that do not seem to be in line with the general picture (even if, herein, it is assumed that the river's flow, changing conditions, sediments, etc. are the responsible dynamic parameters). Carrying out field studies and further research at those points would also support future management for the improvement of the water quality.

6. Conclusions

The present study attempted to enhance the decision-making process for improving water quality by providing a framework for efficient detection of nature-based solutions, in the context of wetland conservation efforts in Canada. We attempted to fill wetland-application gaps and encourage further research on the fair consideration of nature-based solutions in policymaking. An objective GIS-based spatial MCA evaluation framework for the identification of potential wetland-effective areas was presented. We approached the problem at the watershed scale, in order to be holistic and consider the interactions of the system's components in their actual scale, while the criteria used were selected under the perspective to depict the processes of P buffering representatively. To date, wetlands' conversion to farmland is occurring with limited or no background study, because of the limited and case-specific knowledge regarding wetlands' ES potential. We hope that the proposed tool can easily give a picture of their effectiveness spatially, and thus supporting Canadian wetland conservation efforts.

In the Discussion, we argued the credibility of the method, and since it was satisfactory, the proposed tool could be tested in more case studies and by a larger group of experts in order to be effectively established. In the future, more case studies at the watershed, or even at the wetland-specific scale, would be useful, since there is limited experience around the topic. At this stage, the difficulty of validating the results due to the limited work in the field (especially Canada) is a limitation, and it is the main reason for presenting this tool as a preliminary estimator to detect locations of interest. Future research could also consider additional criteria for nutrient absorption, for example, vegetation which is a very challenging task (especially in natural wetlands) as it varies continuously [71]. Scholars with further specialization in chemical processes and nutrient modeling could build on and expand this tool by examining more substances, factors, and techniques. Finally, in the future, having more data and insights from case-specific studies, and a quantitative calibration or validation (e.g., effectiveness of 30, 50, and 70%) of the proposed tool should be implemented to enhance its quality. This would be possible if the inflows and outflows in terms of P loads were known, which could be achieved with a combination of SWAT modeling techniques. This is the reason we developed the proposed framework in GIS, i.e., the compatibility with SWAT for future model-building expansion. Thus, a (more) fair comparison of natural-based solutions with technical solutions (WWTPs) could be (and would be in the future) better established.

The combined tool of GIS-based MCA evaluation could provide a better understanding, a strong database, and guidance for policymakers. Application of the proposed framework in the Grand River watershed is an important first step towards the consideration of wetlands and the provision of scientifically accurate estimations of their potential.

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