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Article

Identifying Feasible Locations for Wetland Creation or Restoration in Catchments by Suitability Modelling Using Light Detection and Ranging (LiDAR) Digital Elevation Model (DEM)

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Received: 28 February 2018; Accepted: 9 April 2018; Published: 11 April 2018

Abstract: Wetlands play a key role in controlling flooding and non-point-source (diffuse) pollution. They are therefore an important tool for mitigating diffuse water pollution from farms. However, to use this tool, it is necessary to obtain detailed assessments and identification of potential wetland restoration or creation sites. This is complicated by the diversity of landscapes, environmental conditions, and land ownership. Site suitability for wetland restoration or creation depends on many factors: the underlying geology, soils, topography, hydrology, drainage, and land ownership. Local hydrology and soils are among the most important factors. However, the inventory and characterization of a site's soils and hydrology often requires extensive, expensive, and time-consuming ground surveys, and it is therefore limited to small areas. Another possibility would be to consider topography, which strongly determines water movement patterns. Light detection and ranging (LiDAR) data provides detailed topographic information and can be acquired by remote sensing. Our study showed that terrain analysis using high-resolution topographical data can produce suitability maps for wetlands that can be easily used by decision makers and planners in watershed management. The rapid methodology reveals potential wetland creation or restoration sites at a reasonable cost; with the resulting spatially explicit suitability map, managers can plan for wetland creation or restoration without having to wait for field-data collection.

Keywords: spatial analysis; suitability analysis; spatial planning; watershed management; GIS; landscape planning

1. Introduction

Water pollution is not only an environmental issue, but it is also an economic and human health problem. Diffuse (non-point-source) water pollution is one of the major problems for water quality in many countries. Wetlands are one of the most effective tools for mitigating pollution, including that caused by nutrient losses from agricultural fields, by trapping and removing sediments and nutrients in runoff before they can enter surface waters [1]. Due to intensifying agriculture, wetlands around the world have been drained and converted into farmland. In New Zealand, it has been estimated that more than 90% of the former wetland area has been lost within a century and a half [2]. The remaining wetlands are fragmented and often degraded [3]. Unfortunately, there is an ongoing trend toward intensified agriculture, and this has raised concerns about the environmental sustainability of this approach, particularly given the resulting contamination of groundwater and surface water with nutrients, particularly in land that is used for intensive dairy farming [4]. Therefore there is an increasing need for effective management tools to reduce nutrient losses and pollutant leaching into water bodies [5]. Recently, wetland restoration and creation have been increasing around the world because of the multiple, valuable environmental services that are provided by wetlands [6], particularly in terms of their ability to trap pollutants and leached nutrients.

The identification of potential sites for creating or restoring wetlands that can provide multiple benefits to large parts of a watershed is increasingly desired to achieve multiple targets, such as reducing downstream nutrient loads, but also controlling storm flows and providing wildlife habitat. However, such a process is complicated due to the spatial diversity of landscapes. Therefore, it is necessary to develop an effective method to support management decisions during watershed spatial planning [7].

Site suitability for wetland restoration or creation depends on many factors: the underlying geology, since wetlands require the presence of unaltered organic layers or lithic strata that are saturated with or impervious to water [6]; topography, since a wetland area needs to be generally flat, but natural landforms, such as swales and gullies, can facilitate wetland construction [8]; availability of the land, since current uses, and land ownership may prevent this form of management; surrounding and upstream land uses, since these will determine the most effective design for pollutant and nutrient removal; the location of the pollution sources; the nature of the drainage systems; and, perceptions of local citizens and landowners. Sites differ in their potential to attenuate pollution from diffuse sources if they are converted to wetlands (i.e., differ in their effectiveness) and in their cost of acquisition and restoration (i.e., differ in their economics) because they need space that is not always available and because farmers do not want to lose productive land. In addition, a wetland may have impacts on infrastructure (e.g., roads, farmhouses) that must be avoided.

Land-use suitability analysis is a useful geographic information system (GIS) application that supports spatial planning [9,10]. GIS-based land-use suitability analysis has been applied in many fields, including defining land suitability or habitat for animal and plant species [11,12], determining the suitability of land for agricultural activities [13], and supporting regional planning [14]. This analysis aims to identify the optimal spatial patterns for future land uses according to specific requirements, restrictions, and plans, but it is often also used for site selection [15]. For site selection, GIS-based spatial analysis is often integrated with multi-criteria evaluation (MCE) techniques (MCE-GIS) to create visualised suitability maps for users and decision makers [10]. MCE-GIS has been successfully used to identify the potential sites for wetland creation or restoration at a watershed scale [7,16]. For example, Babbar-Sebens et al. [17] developed a catchment-scale methodology for identifying the potential sites for wetlands in a tile-drained landscape in the Midwestern United States, and for optimizing the spatial distribution of these wetlands to reduce peak runoff flows. MCE-GIS has even been used to predict the national spatial distribution of wetlands in France [18] and in Denmark [19]. These studies used various spatial datasets (e.g., climate, soils, topography, vegetation), but mostly with low to moderate resolution (e.g., national-level data is often only available at 1:50,000 scale or lower resolution), and although the results were satisfactory or even good, several of the abovementioned studies pointed out that more accurate data would be needed to support environmental management.

Existing wetlands are most commonly detected based on the existing vegetation using remote sensing techniques [2,20,21]. Many species grow only in wetlands and are strong indicators of wetland boundaries [22]. However, if the aim is to delineate areas for potential wetland sites, then vegetation is a poor indicator because drainage or agricultural activities may have eliminated the original vegetation, leaving no clues to the former wetland's existence. Hydrology and soils are also important factors. However, mapping soils and hydrology often demands time-consuming and expensive ground-based surveys [23]. One alternative would be to consider the effects of catchment geomorphology, since topography is the primary driving force for water movement. Since the start of the 21st century, there have been enormous improvements in the techniques for spatial data acquisition. One is the appearance of airborne laser scanning (ALS) technology. Light detection and ranging (LiDAR) is a relatively recent surveying method that can provide very high resolution data over large areas [24]. Using LiDAR data as the basis for terrain analysis could let managers predict the locations of potential wetlands. This approach has the advantage of being systematic, rapid, and able to cover large geographic areas, while providing a high level of detail. Another advantage is that the data is less expensive to obtain than data based on field surveys, and may provide better coverage and higher resolution than satellite data, since LiDAR missions are usually flown in good weather, so that no data is lost due to cloud cover. LiDAR data has been used in previous studies to detect the potential wetland sites, but all of the previous studies have used time-consuming and computationally demanding methods such as hydrological modelling [17] or the Monte Carlo method [25], or have used several additional datasets, such as soil and vegetation data [26], which may not always be available. On the other hand, several studies have used LiDAR data successfully to estimate a landscape's water storage capacity [27], hydrologic connectivity [28,29], and height of wetland vegetation [30,31].

The objective of the present study was to develop a rapid and simple method to map the most feasible locations for wetland creation or restoration sites at a catchment scale, without requiring substantial additional datasets or field-based information. To maintain a manageable scope for our study, we restricted our approach to terrain analysis that is based on LiDAR data, with orthophotos being used as supportive information to provide infrastructure detection. Our aim was to first determine the most suitable areas for wetlands using GIS-MCA, thereby letting us visualise the spatial distribution of suitability for wetlands in a single suitability map, and second, to identify specific flow-interception points where impoundments could be established to create wetlands with an optimal depth and size for nutrient removal.

2. Materials and Methods

2.1. Study Area

Our study area was in the Waituna Lagoon Catchment, which is situated on the southern coast of South Island, New Zealand (Figure 1). The Waituna Lagoon Catchment comprises three subcatchments: Waituna Creek, Moffatt Creek, and Carran Creek. The current study was carried out in one of the subcatchments of Waituna Creek. The study area has a gently rolling relief. The brown soils are intensively drained to enable grazing by dairy cattle. Increasing agricultural development and intensification in the catchment has been implicated in declining water quality. A range of management actions to reduce nutrient runoff is now being considered to address these problems [25].

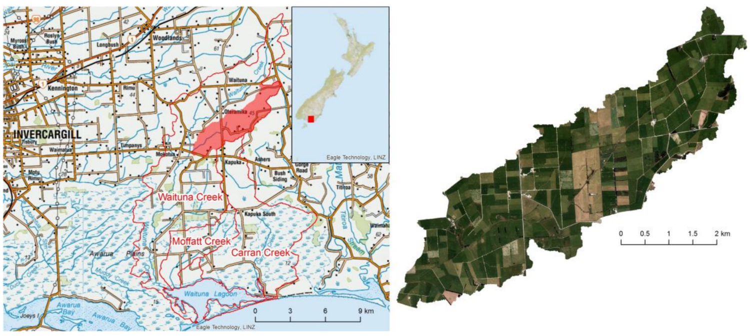

Figure 1. Study area (marked red) in in the Waituna Creek Catchment and orthophoto showing land use.

2.2. Criteria for Wetland Creation or Restoration and Spatial Analysis

We defined the following criteria at the beginning of the assessment process for use in the GIS-MCA:

- Tile drain flows are the dominant hydrologic flow paths in the area, and the drains commonly follow natural drainage channels. Therefore, wetlands that are sited in these locations are also likely to intercept a high proportion of surface and subsurface run-off during large rainfall events [32]. Therefore, we only considered in-stream options in the current study (i.e., options in which the stream flows through or is closely adjacent to the wetland). In addition, in-stream wetlands require less investment than off-stream alternatives, and are a good option if the restoration budget is limited.

- The contributing area (i.e., the area that contributes water to the wetland) is an important criterion, since wetlands with a too-small contributing area may be ineffective for decreasing pollutant loads. (Here, we will focus on nitrogen pollution, but the same approach applies to most other pollutants.) The minimum area we chose for this study was 50 ha.
- It has been proposed that the relative area of wetlands that is required to effectively remove excess nutrients is in the range of 0.1 to 5.0% of the catchment's contributing area [32,33]. We therefore chose a potential percentage of the wetland ranging from 1 to 5% of the catchment area.
- The recommended operational depth of the wetland is between 0.1 and 2.0 m [34], with the recommended average ranging between 0.5 and 0.7 m [35]. We therefore chose an operational depth ranging from 0.1 to 2.0 m.

We used a digital elevation model (DEM) with 1-m resolution from LiDAR data provided by Environment Southland. We hydrologically corrected the DEM by finding the sinks and filling them to create a depressionless DEM in ArcGIS 10.2 for delineating the stream network [36]. We removed any artificial impoundments that were formed by roadways by finding the intersections between roads and streams using spatial queries. The artificial impoundments were decreased ('burned') to 1 m below the channel elevation to obtain the corrected DEM (Figure 2).

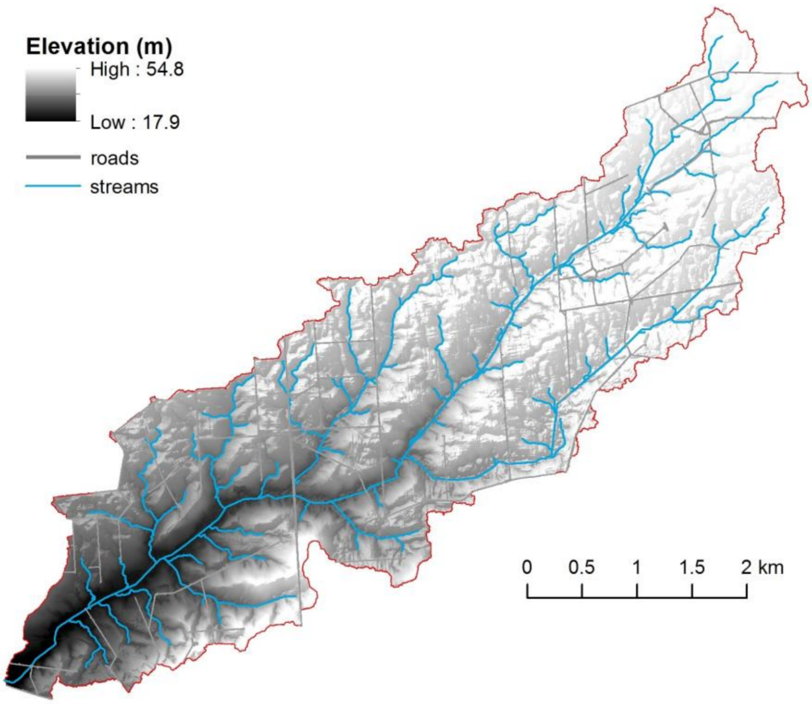

Figure 2. Shaded digital elevation model (DEM) of the study area based on light detection and ranging (LiDAR) data. Roads and streams with a contributing area ≥5 ha are also shown.

First, we calculated the flow direction from the corrected DEM in ArcGIS 10.2 using the eight-direction (D8) flow model that was presented by Jenson and Domingue [37]; in this model, there are eight potentially valid output directions for each cell (i.e., flows to the eight adjacent cells). Flow direction was used as an input to calculate flow accumulation (Figure 3). By applying a threshold value to the results of the flow accumulation, we delineated a virtual stream network that represented the potential flows based on the topography. All streams that had a contributing area of at least 5 ha were delineated. In practice, an actual stream may not exist in many of the places that were shown in the virtual network, but an area of convergent flow will nonetheless exist during rainfall events, and subsurface drainage will typically either be connected to or will follow these flow pathways. We used the inferred surface drainage networks to estimate the catchment areas at a higher elevation than the prospective wetland sites and calculate the appropriate wetland drainage areas.

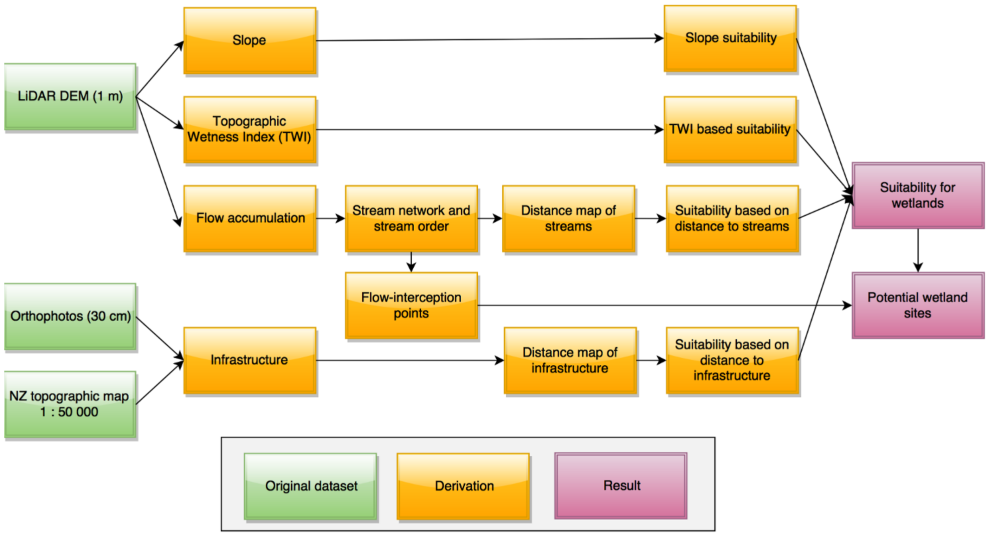

Figure 3. Workflow used for processing of the digital elevation model (DEM) data to generate suitability maps for mapping feasible locations for wetland construction or restoration.

We only considered in-stream options in the present study, but off-stream wetland options might be appropriate in some areas. However, they have the disadvantage that they would generally only intercept a portion of the overall flow, and would therefore receive and remove less of the pollutant load. Therefore, the potential wetland sites in our analysis occurred along the streams or drainage ditches, and there is a higher probability for suitable wetland sites to exist along the higher-order streams. We calculated the Strahler [38] stream order based on the virtual stream network, and then used these orders to define stream size based on a hierarchy of tributaries. In this approach, first-order rivers (rivers without tributaries) are the outermost tributaries, with no tributaries of their own. When two upstream links of the same order join, the downstream link order increases by 1. When two upstream links of different orders join, the downstream link takes the higher order of the two incoming upstream links. Strahler streams are segments of a channel that consist of links of the same order. We created distance maps with a maximum distance of 125 m from the streams, and converted them into suitability maps with each pixel having values from 0 to 1. The closer a site is to a higher-order stream, the higher its suitability as a wetland site. In addition, the suitable area around higher-order streams was wider than around the lower-order streams.

We also calculated several derivatives from the original DEM, with the fill function not being applied (Figure 3). Slope was the simplest derivative, since low slope angles are more suitable for wetlands than steeper slopes. However, in New Zealand, wetlands can also occur on steeper slopes. Therefore, in the current study, we defined the maximum suitable slope for wetland as 3°. Smaller slopes were assigned a higher suitability for wetland development.

In addition to the slope, we calculated the topographic wetness index (*TWI*; Equation (1)). *TWI* is a function of both the slope and the upstream contributing area per unit width orthogonal to the flow direction [39]:

$$TWI = \ln \frac{a}{\tan b} \tag{1}$$

where a is the specific upslope area draining through a certain point per unit contour length ($m^2\ m^{-1}$) and b is the slope gradient (in degrees). Higher TWI values indicate higher soil moisture content and also a higher suitability for wetland. *TWI* has been used effectively to predict soil moisture and has also been tested for identifying wetlands by several authors [23,40]. However, *TWI* alone did not provide sufficient results. Therefore, we used *TWI* only as one parameter. *TWI* was calculated using SAGA GIS [41]. Values of *TWI* were divided into deciles and assigned values from 0 to 1 to create a suitability map.

In the context of our study, we defined constructing or restoring a wetland as flooding the suitable area. Flooding of infrastructure (e.g., roads, farmsteads) within that suitable area should be avoided, therefore we needed infrastructure data for our study area. Because there is currently no reliable method for identifying infrastructure from LiDAR data, we extracted the main roads from the New Zealand digital topographic map (https://www.linz.govt.nz/land/maps/topographic-maps) (1:50,000). However, the topographic map was not detailed enough to identify smaller roads and farmsteads. We therefore used orthophotos with a 30-cm pixel size [42] for a more detailed analysis of the infrastructure information. We used supervised image classification to classify the image pixels, and used a majority filter for clean-up [43]. We applied multiple 10-m buffers up to a distance of 100 m from the infrastructure. The buffer values were converted into a suitability map in which distances from the road were assigned values starting from 0 m (beside the road) and ending with 1 at a distance of 100 m from the road. We used the NZ Cadastral Parcel dataset [44] to identify the cadastral units and orthophotos to identify existing wetlands.

2.3. Suitability Modelling Approach

We used a multi-criteria evaluation (MCE) approach that was designed to identify the spatial distribution of the sites most suited to wetland creation or restoration. MCE is a methodology that combines criteria from different sources of information into one overall evaluation index [45]. MCE has its origin in planning, but its integration with GIS means that it is commonly used in suitability modelling [46,47]. We employed the simplest of these techniques, namely linear-weighted summation, in which all of the weights were treated as equal to calculate the final score for wetland suitability:

$$Score = \sum_{i=1}^{n} w_i V_i \tag{2}$$

where n is the number of criteria, V_i is the value associated with criterion i, and w_i is the weight associated with criterion i. We used four criteria from the spatial analysis: slope, *TWI*, distance to streams, and distance to roads. We standardised each criterion value between 0 and 1 by splitting them into quantiles.

2.4. Delineation of Potential Wetlands

We defined a basic wetland design that used a low impoundment that would flood the drainage ditch and some of the surrounding flat land. This approach takes advantage of the natural landscape and it is likely to be the cheapest construction method. For each stream that had a drainage area of at least 50 ha, we identified a flow interception point where lower-order or same-order streams with a contributing area of at least 5 ha joined the stream. We used these interception points together with a combined wetland suitability map to determine the possible sites to create an impoundment. We initially set the impoundment height to 1 m above the ditch bank. Based on the DEM, we used SAGA GIS [41] to calculate the potential wetland area that was virtually flooded from the impoundment up to a depth of 1 m. We calculated the area, average depth, and water storage capacity for each modelled wetland based on the flooded area.

3. Results and Discussion

Figure 4 shows the potential suitability maps that we developed based on the slope, *TWI*, distance to infrastructure, and distance to streams. According to the final wetland suitability map that we generated from these maps (Figure 5), 14% (220 ha) of the catchment was highly suitable for wetland construction or restoration, with a suitability value >0.75. Highly suitable areas were mostly associated with streams that had an order of 2 or more because we focused only on in-stream wetlands. However, the upper catchment, in the northeast, had flatter topography and therefore had a higher proportion of areas that were highly suitable for wetlands that extended a greater distance from the streams. The lower catchment is hillier, with steeper slopes and also with more infrastructure, which results in having highly suitable areas only in the gully bottoms. 30% of the catchment area is not suitable (suitability value < 0.5) for wetlands, mainly because of the steep slopes and the presence of infrastructure. We also identified existing wetlands. All except one (a large wetland in the northeastern part of the study area) were located in a river gully. The existing wetlands were remnants and were located in the same areas that we rated as having a mostly high or moderate suitability value. The current methodology aimed to detect the suitable areas for wetland creation and restoration. However, there were several cases where the existing wetlands were adjacent to roads and which we would consider to be less suitable for restoration based on our infrastructure criterion. Therefore, existing wetlands did not always fully coincide with the highly suitable areas revealed in our analysis.

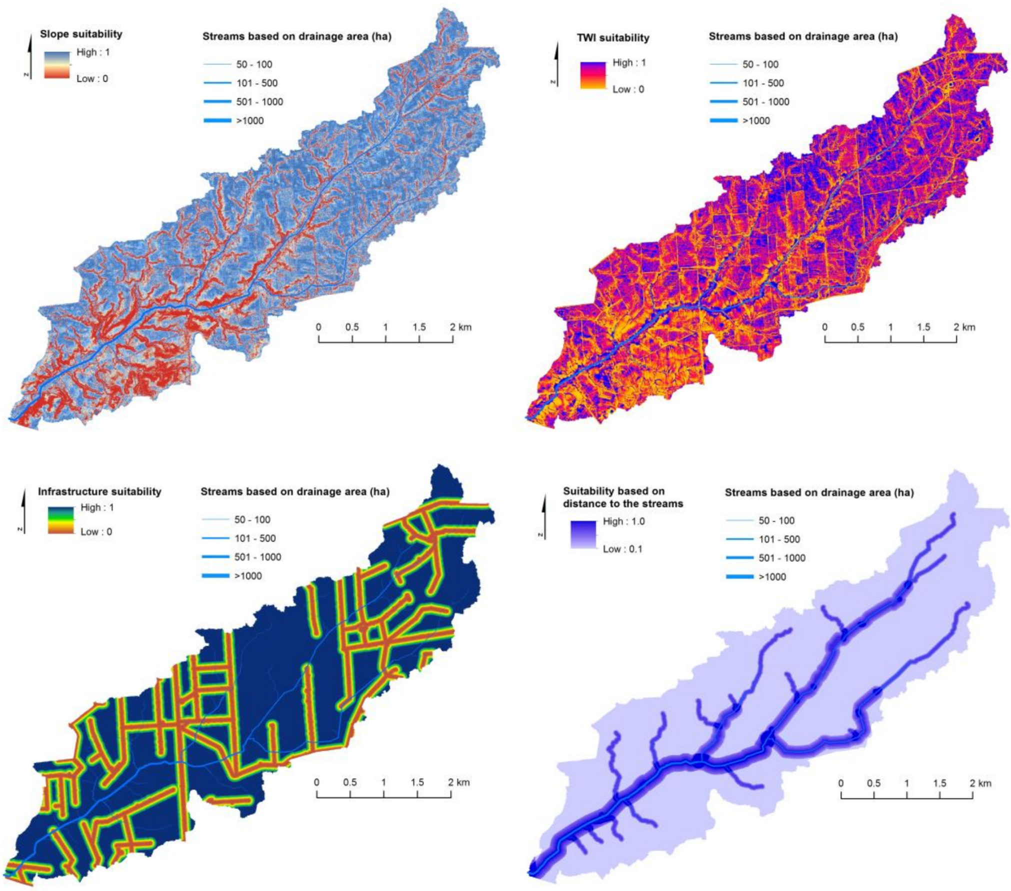

Figure 4. Suitability maps used to create the final wetland suitability map. *TWI* represents the topographic wetness index, and "infrastructure" represents the distance to the nearest road, farmstead, or other human structure that must be protected against flooding.

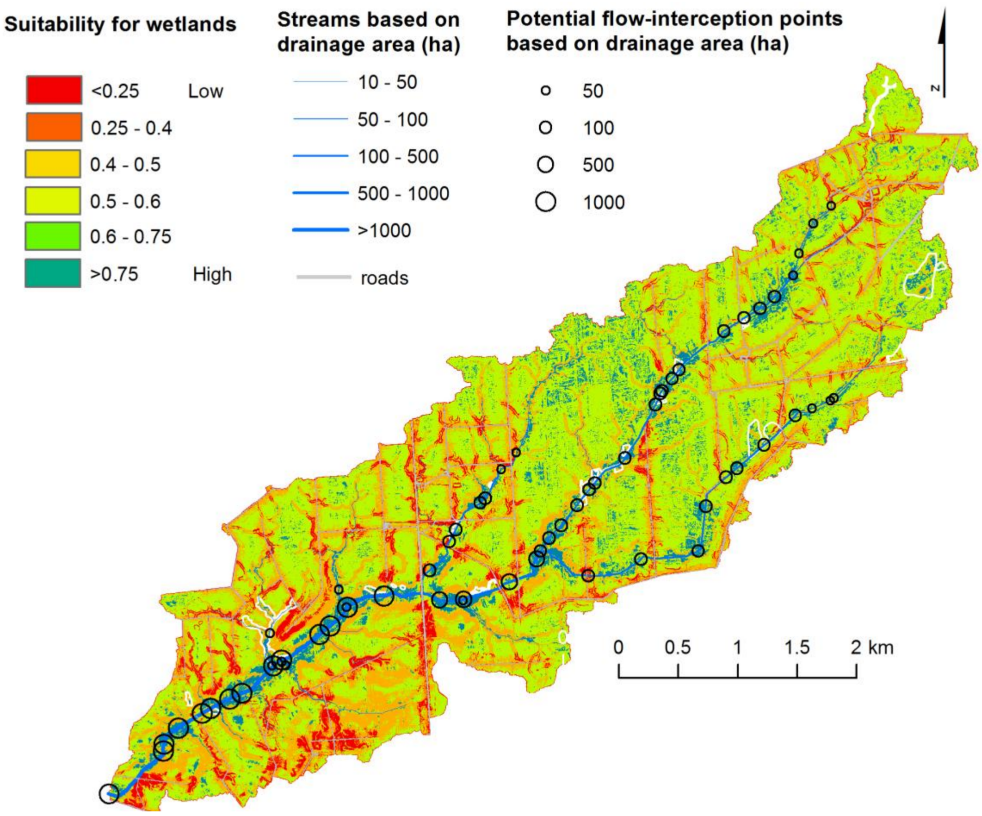

Figure 5. Final suitability map for wetlands and the potential flow-interception locations based on the size of the drainage area and the four criteria-based suitability maps in Figure 4. The existing wetlands that were identified from orthophotos are colored white.

We identified 64 potential interception locations in streams that had a drainage area larger than 50 ha (Figure 5). Several of them were very close to each other in the higher-order stream in the southwestern part of the study area due to the incoming first-order streams. However, many of them did not have a sufficiently large area adjacent to a stream to consider them as potential sites for wetland construction or restoration. Where interception points coincided with a larger area of highly suitable land, we delineated a potential wetland. Figure 6 shows the flooding characteristics of six potential locations for wetlands that could reduce nutrient runoff, and Figure 7 shows their locations within the catchment. Those wetlands did not affect existing infrastructure, and together covered 1.7% of the whole catchment (Table 1), which we considered to be optimal for water quality improvement based on the criteria discussed in the Methods. The upper catchment wetlands covered a higher proportion of their drainage area (up to 3.3%) and were shallower than those in the lower catchment, mainly because of the flat topography in that area. Interestingly, two of these sites (W5 and W3) were still wetlands just 10 years ago. For example, based on historical Google Earth remote sensing imagery, potential wetland site W5 was still wetland in 2003, and even in 2015, some remnant wetland was present in this area (Figure 8). All of the other sites had either small remnant wetlands present within their area or in the close vicinity of that area, indicating that these areas have been wetlands recently. Obviously, farmers have recently invested considerable effort in draining these areas, and farmers will therefore be understandably reluctant to return these areas to wetland. This shows the importance of increasing awareness of the potential value of natural wetlands for contaminant attenuation by intercepting run-off and the need for early intervention before farmers have invested large sums of money in wetland drainage [32].

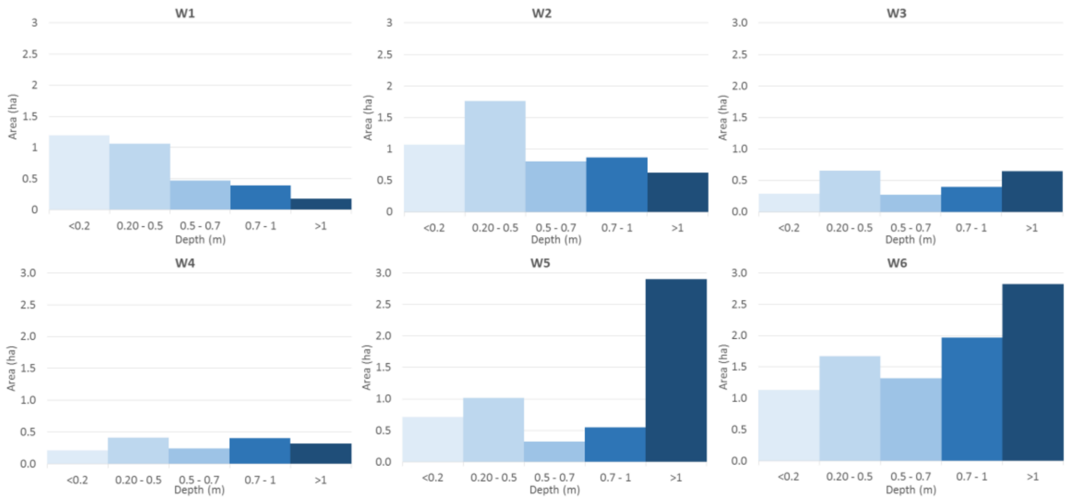

Figure 6. Histograms of the wetland depth distribution in the six potentially suitable wetland areas. Locations of the areas are shown in Figure 7.

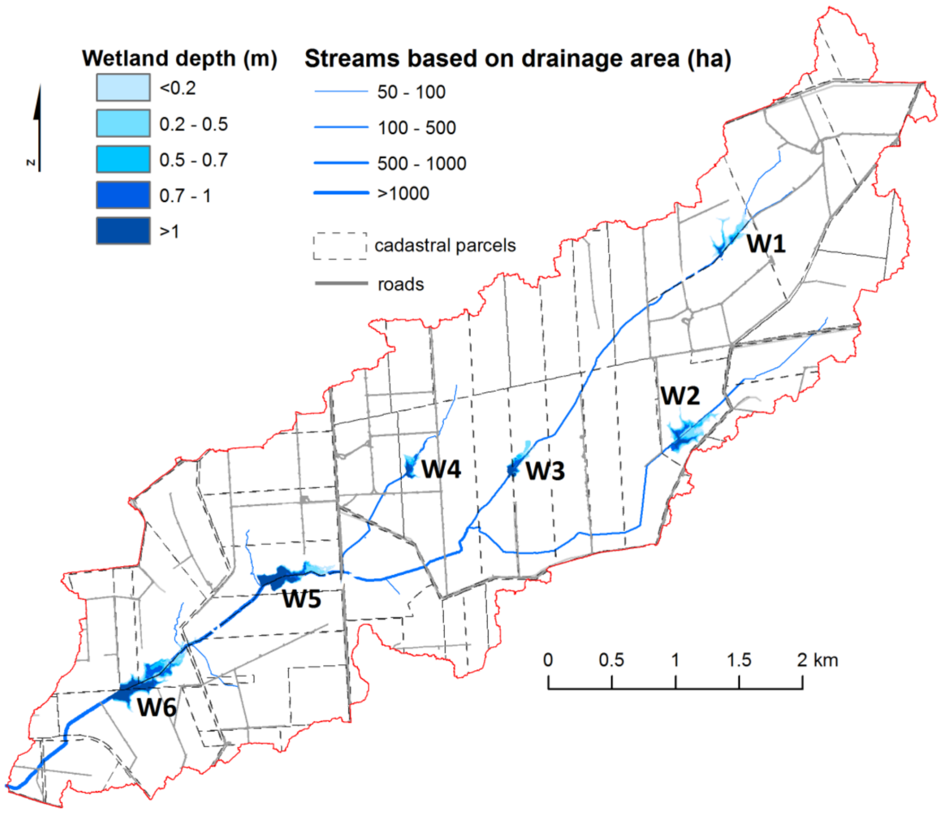

Figure 7. Six potential wetland sites delineated based on the wetland suitability map, along with cadastral information.

Table 1. Main characteristics of the six potential wetlands identified in the present analysis. Figure 6 shows the areas of these wetlands for different flood depths, and Figure 7 shows their locations within the catchment.

Wetland ID	Contributing Area (ha)	Wetland Area (ha)	Proportion Within the Catchment (%)	Average Depth (m)	No. of Cadastral Parcels	Water Storage Capacity (10^3 m^3)
W1	175.3	3.3	1.9	0.4	1	13.0
W2	155.7	5.2	3.3	0.5	1	27.5
W3	455.4	2.4	0.5	0.7	2	17.8
W4	133.8	1.6	1.2	0.7	1	11.1
W5	1115.1	5.5	0.5	1.0	2	61.3
W6	1484.8	8.9	0.6	0.8	5	73.2
Total	**1584.5**	**26.9**	**1.7**			**203.9**

Figure 8. Potential wetland site W5 in 2003 and in 2015. The red line indicates the modelled potential wetland area.

We predicted that these six wetlands would have the potential to store 204 $\times$ 10^3 m^3 of water. From a landscape perspective, wetland water storage is known to decrease the magnitude and frequency of flood events, and also to improve downstream water quality through increased water residence times [27,48]. The residence time of a wetland can be lengthened by increasing its surface area or volume [33,35]. All of the potential wetlands had a water depth between 0.1 (the minimum operational depth in our criteria) and 2.0 m, except for the drainage channel, which was 2.0 to 4.0 m deep in most cases after flooding (Figure 6). In most cases, the average depth of the wetlands was between the initially suggested water depth (0.5 and 0.9 m). However, in some cases, areas that were too deep (>1.0 mm) or too shallow (<0.5 m) occupied a larger-than-optimal proportion of the wetland. In the upper catchment, the topography was too flat; so two wetlands (W1 and W2) were shallower than the optimal value. In two wetlands (W5 and W6) that were located in the lower catchment, the water was deeper than optimal because the steep slopes of the gullies prevented us from designing a wetland that would flood a big enough area without the water getting too deep. The potential wetland sites therefore depended strongly on the natural topography, and it would be a complicated challenge to achieve a consistent depth throughout the wetland areas. Another factor to consider is that the water depth in the wetlands may decrease over time due to the accumulation of sediments, including detrital plant material. The water depth could be increased by increasing the impoundment height, although this would affect the potentially suitable area if (for example) this brought the flooded wetland too close to existing infrastructure. It would also increase the construction cost and the subsequent maintenance costs. From the perspective of flood control, it has been argued that small wetlands located in the upper portion of a watershed and that drain only a small percentage of the total contributing area may have little impact on downstream flood peaks and runoff volume [49]. On the other hand, it has been shown that small headwater wetlands can be very efficient in reducing flood risk if they can be excavated up to 0.5 m deeper and can increase water storage by doing this [17].

This would also be an option for the two shallower headwater wetland sites (W1 and W2) that were identified in this study.

The spatial location of planned wetlands will depend on the pollutant being targeted [35]. Some studies have suggested that the wetlands should be located as close to the pollution source as possible in the upper catchment, at the outlet of the sub-catchment [50]. This agrees with the findings of Peterson [51] who showed that the most rapid uptake and transformation of inorganic nitrogen occurred in the small headwater streams in the upper catchment. However, Tanner and Kadlec [52] have shown that the wetland performance for nitrate-N will generally be better near the bottom of the catchment, where flow regimes tend to be more buffered than they are at the top of the catchment because the wetlands receive steady flows of diffuse nitrate-rich run-off (i.e., a high proportion of consistent base-flow). They will show the best nitrate-N removal performance. This can also support the practical side of wetland management: one large, collectively managed wetland, could be more practical than several smaller ones in some cases [53]. In our study, the wetland at the very lower part of the watershed (W6) belonged to five different cadastral parcels, meaning that managers of these five areas must collaborate in creating and managing the wetland. At the same time, farmers are not interested in losing too big a proportion of their farmland at one location to wetland restoration. Having one large wetland at the outlet of the catchment might mean that only one or two farmers are responsible for water quality in the whole catchment, since the wetland is located only on their property. This can reduce their willingness to participate in wetland restoration or creation if they are not given additional incentives (e.g., tax incentives). Also, in the case of one large wetland, there is a higher probability of land-use conflicts, such as the flooding of infrastructure. This suggests that there is a need for stakeholder involvement when planning the final location of wetlands to ensure that all of the potential issues can be identified and solutions can be proposed. Since not all of the conflicts can be resolved, it might be more reasonable to spatially distribute the wetlands within the catchment.

Soils are considered to be a good indicator for wetland mapping. Wetland soils often contain large amounts of organic matter and their properties reflect the long-term hydrology and are, therefore, useful in identifying wetlands even where the natural hydrology and plant community have been disturbed by drainage [54]. However, we did not consider soil data because in New Zealand, as in most countries, soil maps are only available at a scale of 1:50,000 or an even coarser resolution, which is too coarse for delineating small-scale wetlands. The soil map is usually constructed based on field soil investigations, but an important part of the delineation of soil polygons is the assessment of other related environmental data, such as topography, geology, geomorphology, vegetation, land cover, and climate [55]. The soil investigations are only conducted at limited locations, and the spatial variation of the soil properties is then inferred and mapped using different approaches, including computer-generated output from a statistical analysis of data (e.g., complex interpolation schemes) through to someone drawing lines where the interpreter believes that a change occurs, and two-dimensional cross-section diagrams showing the relationships between soils and landforms. Therefore, soil data is often considered to be secondary data that might be insufficiently precise to support assessments of the suitability of an area for a small-scale wetland.

GIS-MCE is a relatively straightforward technique, and it combines and transforms spatially explicit data (inputs) into a resultant decision (output) [9]. The MCE rules (criteria standardisation and weighting) define a relationship between the input maps and the output map. However, these rules reflect the decision maker's subjectivity to some extent. It has been shown that different standardisation methods and weights can lead to very different suitability maps [56]. Therefore, the standardisation and the assigning of weights should be done with care. In the current study, we used equal weights to reduce the sensitivity of our analysis to a higher weight for one or more criteria [57]. In future research, it will be necessary to find ways to objectively determine the optimal weighting for each criterion.

Another important limitation of the current method is that it identifies the potential sites for only one specific type of wetlands (i.e., in-stream riverine wetlands), and it might not work well for other types of wetlands (e.g., depressional wetlands) or in areas with flat topography. As our goals were to find wetlands that would potentially intercept the highest nutrient loads and to facilitate their design by creating only an impoundment in the rivers, we only considered in-stream options. Furthermore, we utilized contemporary topographic data, which reflects a high degree of anthropogenic modification by drainage, and which does not directly capture the historical distribution of wetlands [27,58]. Another potential source of uncertainty is related to the use of LiDAR technology, which might lower the accuracy of the DEM in areas with dense vegetation [59]. However, our study area was mostly covered by grasslands and lacked areas with high vegetation density.

Our analysis let us identify the potential wetland creation or restoration sites using only topographic and land use data acquired by remote sensing (i.e., LiDAR and orthophotos). The resulting spatially explicit wetland suitability map provided a good information base to support final site selection. However, all of the potential sites should be validated by means of field topographic and soil surveys, thereby confirming the probability of temporary water storage and characterizing the soil layers to ensure that the natural hydraulic conductivity will be suitable for water retention.

4. Conclusions

In this study, we combined GIS with multi-criteria decision analysis to find feasible locations for wetland creation or restoration, with the goal of using the wetlands to improve water quality in a catchment. We used a high-resolution LiDAR DEM and orthophotos to derive suitability maps that accounted for four important criteria (slope, *TWI*, and the distance to infrastructures and streams). We then used multi-criteria evaluation to combine the suitabilities based on all four criteria into a single wetland suitability map. Using this method, we identified six final sites that accounted for an optimal proportion (1.7%) of the watershed, based on their flow interception locations and the suitability map.

Such new monitoring techniques, with high spatial resolution, offer improved opportunities to analyse flow paths and to determine suitable locations for wetland creation or restoration without requiring the use of additional data sources, such as field soil survey data. Implementation of this method can improve watershed management by speeding up the decision making process and making it more cost-effective.

Acknowledgments: Evelyn Uuemaa thanks New Zealand's National Institute of Water and Atmospheric Research for hosting her for 2 years, and is grateful for funding from the Marie Skłodowska-Curie Actions individual fellowships offered by the Horizon 2020 Programme under Research Executive Agency, grant agreement number 660391, the Ernst Jaakson memorial stipend by the University of Tartu Foundation, and institutional grant no. IUT 2-16 by the Estonian Ministry of Education and Research. We thank Environment Southland for providing the LiDAR data. We also thank Geoff Hart for language editing and the anonymous reviewers for insightful comments on the paper, as these comments improved our work.

Author Contributions: Chris C. Tanner and Andrew O. Hughes conceived the study; Evelyn Uuemaa performed the analysis; Evelyn Uuemaa, Andrew O. Hughes and Chris C. Tanner wrote the paper.

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

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