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Modelling Surface Water Susceptibility to Pollution Using GIS

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Abstract

This research is an attempt to develop a new GIS index to investigate the surface water susceptibility to pollution (SWSi). In this index, the Weighted Linear Combination techniques within GIS environment was used to calculate the overall surface water susceptibility to pollution scores based on using 6 factors. The model includes 3 natural factors: gradient slope, distance to surface water and soil. Also, it includes 3 man-made activities: urban, agriculture and roads. Each factor was given the appropriate weight and ratings and then the final index was calculated using GIS techniques. The final results showed that the study area (1235 km^2) could be classified into low susceptibility with an area of 250 km^2 (20.2%), moderate susceptibility with an area of 815.5 km^2 (66%), high susceptibility with an area of 166.2 km^2 (13.5%) and very high susceptibility with an area of 3.3 km^2 (0.3%).

Keywords

GIS, WLC, Surface Water, Susceptibility, SWSi

1. Introduction

The assessment of surface water resources susceptibility to pollution is important for drawing pollution risk maps [1]. There are several studies to investigate surface water susceptibility to pollution worldwide ([1]-[7]). These studies intended to design models and indices to estimate the surface water susceptibility to pollution similar to groundwater vulnerability indices [1]. The major factors used in these studies were slope, land use, land cover, distance to water sources and groundwater contribution, and all these studies used indices to estimate the surface water susceptibility to pollution within GIS environment. GIS is used to quantify sensitivity and potential pollution variables that may affect surface water quality within areas contributing water to surface water sources.

Jordan is currently one of the poorest countries in the world in terms of water resources. It is characterized by arid climate, with more than 90% of its area receiving less than 200 mm rainfall annually. In Jordan, surface water is considered as a major source for household and agricultural usages. It is the major supplier to the agricultural sector and it is the second largest source for household consumption. The annual supply of surface water in Jordan is 214.69 million m^3. This precious source of water is not invulnerable to pollution. Surface water resources systems are subject to several man-made pollution impacts. Surface water in Jordan suffers from various sources of pollution. The polluted surface water resources are often those lying within or downstream of urbanized and industrialized areas, as well those surrounding irrigated lands (use and overuse of fertilizers, pesticides and insecticide) ([8] and [9]).

This research is an attempt to modify existing surface water susceptibility to pollution indices based on the available literature. The modified index will be tested on a study area in the Northern part of Jordan.

2. Research Methods

2.1. Study Area

The selected study area for this research is located in the Northern part of Jordan (**Figure 1**). It is on the border with Syria and has an area of 1235 km^2, which comprises approximately 1.4% of the total area of Jordan. The study area has several towns and villages (**Figure 2**) with an urban area of 31.74 km^2 which is approximately 2.57% of the study area. The agricultural area (**Figure 2**) within the study area is 27.76 km^2 which comprises approximately 2.25% of the study area. The agricultural activities in the area include growing vegetables, fruits and olives [10]. Most of farmers use excessive amounts of fertilizers and pesticides [11].

The study area is mainly flat, where elevation varies between 642 m above sea level in the South to 1224 m above sea level near the Syrian border in the North (**Figure 3**). The average gradient for the study area is less 2%.

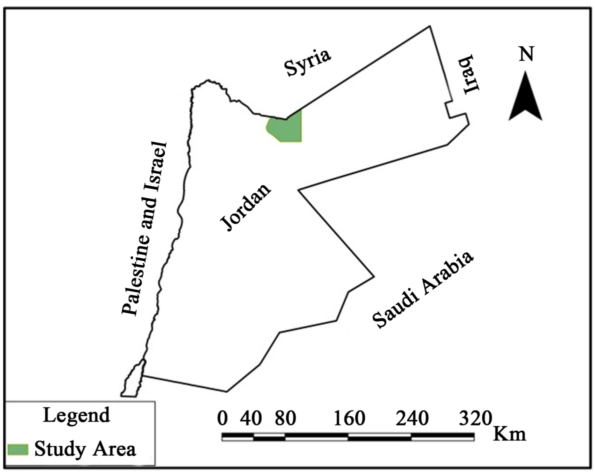

Figure 1. The study area location.

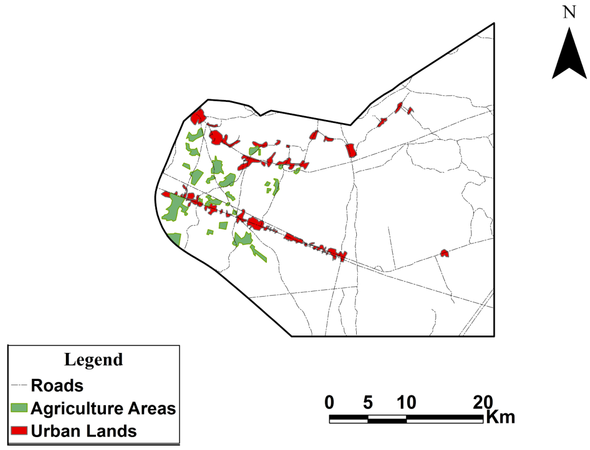

Figure 2. Urban, agricultural lands and roads.

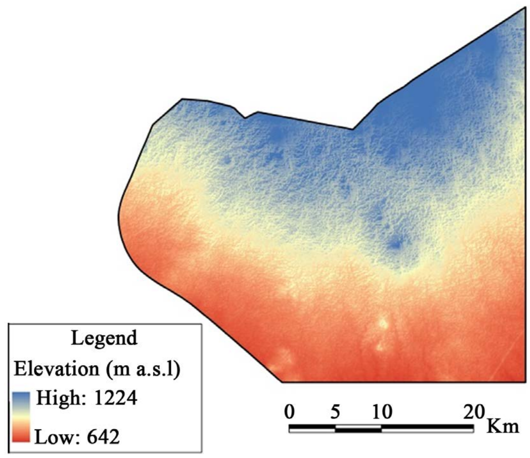

Figure 3. Digital elevation model.

Surface water in the area is mainly from rainfall that occurs between November and March annually. The area receives approximately 250 million cubic meter of rainfall on annual basis. Most of the rainfall is lost due to evaporation (approximately 90%), while only 5% of rainfall generate runoff. The generated runoff flows through the Wadis (streams) that runs mainly from the North towards the South, South East and the South West (Figure 4). Surface water within the study area suffers from various sources of pollution. Among these sources are the followings [11]:

1. The use of fertilizers, pesticides, insecticides and herbicides by farmers in the area.
2. Runoff generated within urban areas which carryout garbage and other pollutant substances to the nearby Wadis.
3. Use of vehicles with oil spills, lead and corroded particles.

2.2. SWSi Development

There are few mythologies developed in the USA to investigate surface water susceptibility to pollution. Among these methodologies are the followings:

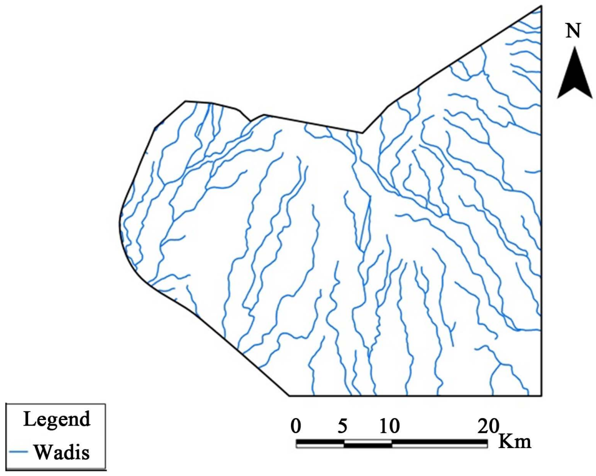

Figure 4. Wadis (Streams) network.

- A methodology by [5] which defines surface water susceptibility to pollution based on 5 factors. These factors include river network, soil, urban distribution, land cover and slope.
- An overlay and index methodology developed by the USGS for rating the characteristics of a watershed [2]. It is based on using 5 factors including average annual precipitation, land surface slope, land cover, land use, and groundwater contribution.
- A methodology developed by [3] that allows the evaluation of the watershed susceptibility to surface water pollution based on major characteristics of a watershed and land uses. It is based on 7 factors including wastewater discharges, recreational land use impacts, agricultural land use impacts, size of watershed, transportation avenues, industrial land use impacts and the amount of vegetation Cover.
- A methodology developed by the Laboratory for Spatial Analysis and the Geosciences at the University of Minnesota-Duluth, USA ([4] and [6]). This methodology was initially developed in 2003 to investigate the surface water susceptibility to pollution from non-point sources. It is based on a fundamental principle that areas with more prone to runoff are capable of transporting suspended sediments to water bodies. Only four intrinsic factors are involved in the estimation of surface-water runoff potential for any given study area using GIS techniques. These factors are gradient slope, distance to water (streams and lakes), land cover and soil properties. Each factor has a weight to reflect its' contribution to surface-water runoff and therefore a general indication of surface water pollution potential.

In this research, a modified methodology will be introduced by having the factors that might influence surface water susceptibility to pollution. The modified index (SWSi) has 6 factors; including gradient slope (%) (GS), distance to Wadis (streams) (DW), soil clay (%) (SC), distance to agricultural lands (DA), distance to urban areas (DU) and distance to roads (DR). In order to allocate the appropriate weight for each factor, 7 experts in the field of surface water quality from various Jordan Universities and organizations were invited to assign a weight for each factor. Experts were asked to give 6 for the factor that has the highest impact on surface water pollution and 1 for the lowest impact factor. A methodology adopted by [12] was used to come up with a single weight for each factor and overcome the variation between experts' weights allocation. The methodology is based on using both the Mean and Median for experts responses and decides the appropriate weight for each factor. **Table 1** summarizes factors weights suggested by the experts. Based on this Table, weights were given to these factors based on each factor contribution to the surface water susceptibility to pollution. The Median value for each factor was selected to represent the appropriate weight for the six factors used in this research. The Mean values also show that the selected weights are reasonable.

The highest weight (6) was given to the gradient slope (GS) (%), while the lowest weight (1) was given to distance to roads (DR). **Table 2** summarizes the classes, weight and ratings for each factor. The justification for using these factors could be summarized as follow:

1. **GS**: Surface water runoff occurs whenever there is excess water on a slope that cannot be absorbed into the soil or is trapped on the surface. The steeper the slope of a field, the higher potential for runoff [13]. Surface water is more susceptible to pollution when runoff is high and infiltration is low [4]. In this research, GS was classified into 5 classes based on [4] (**Table 2**).
2. **DS**: It is an important factor in determining whether surface water is susceptible to pollution or not. In this research a modification to distances suggested by [4] was carried out through the use of meters instead of feet and classify the distance into 5 classes instead of 6 classes (**Table 2**).
3. **SC**: High clay contents' soils have several properties that might lead to the movement of pollutants from agricultural lands. Also, surface structure of soils can become degraded in high clay contents' soils. This will lead to the formation of crust which restricts infiltration and increases runoff. Runoff increases when clay soils are wet, due to soil compactness. The runoff may contain pollutants and could affect the surface water quality [14]. In this research, SC were classified into 5 classes as listed in **Table 2**.

Table 1. Weights given by experts.

Factors	Experts							Mean	Median
	Ex1	Ex2	Ex3	Ex4	Ex5	Ex6	Ex7		
GS	6	6	5	5	6	5	6	5.57	6
DW	5	5	6	6	5	4	5	5.14	5
SC	3	4	4	3	4	6	4	4.00	4
DA	4	3	3	4	3	3	3	3.29	3
DU	1	2	2	2	2	1	2	1.71	2
DR	2	1	1	1	1	2	1	1.29	1

Table 2. Weight and ratings for the SWSi.

GS				DW			
(%)	Weight	Ratings	W × R	Distance (m)	Weight	Ratings	W × R
>20		5	30	≤50		5	25
>10 - ≤20		4	24	>50 - ≤100		4	20
>5 - ≤10	6	3	18	>100 - ≤200	5	3	15
>2 - ≤5		2	12	>200 - ≤500		2	10
≤2		1	6	>500		1	5
SC				DA			
Clay (%)	Weight	Ratings	W × R	Distance (m)	Weight	Ratings	W × R
>30		5	20	≤500		5	15
>25 - ≤30		4	16	>500 - ≤1000		4	12
>20 - ≤25	4	3	12	>1000 - ≤2000	3	3	9
>15 - ≤20		2	8	>2000 - ≤5000		2	6
≤15		1	4	>5000		1	3
DU				DR			
Distance (m)	Weight	Ratings	W × R	Distance (m)	Weight	Ratings	W × R
≤500		5	10	≤500		5	5
>500 - ≤1000		4	8	>500 - ≤1000		4	4
>1000 - ≤2000	2	3	6	>1000 - ≤2000	1	3	3
>2000 - ≤5000		2	4	>2000 - ≤5000		2	2
>5000		1	2	>5000		1	1

4. **DA**: The agricultural non-point source (NPS) pollution is the leading source of water quality impacts on rivers and lakes [15]. DA were classified into five classes as listed in **Table 2**.
5. **DU**: Urban area is one of the most harmful factors affecting surface water health and a major challenge facing watershed managers. Urban runoff affects water chemistry by changing heavy metals and nutrients levels such as phosphorus and nitrogen [16]. DU were classified into five classes as listed in **Table 2**.
6. **DR**: Highway run-off could be identified as a major source of diffuse pollution that might contaminate surface water [17]. In this research, DR were classified into five classes as listed in **Table 2**.

The governing equation (Equation (1)) for the modified index (SWSi) is shown below:

$$\begin{aligned} \text{SWSi} = {} & \text{GSw} \times \text{GSr} + \text{DSw} \times \text{DSr} + \text{SCw} \times \text{SCr} \\ & + \text{DAw} \times \text{DAr} + \text{DUw} \times \text{DUr} + \text{DRw} \times \text{DRr} \end{aligned} \tag{1}$$

where GS: Gradient Slope (%), DS: Distance to Surface Water, SC: Soil Clay (%), DA: Distance to Agricultural Lands, DU: Distance to Urban Areas, DR: Distance to Roads, w: Weight and r: Ratings.

The overall index calculation could be classified into 4 susceptibility classes as listed in Table 3 (Low, Moderate, High and Very High).

2.3. Data Collection

Dada required for this research were collected from several governmental agencies in Jordan and international agencies. Table 4 describes these dada and their sources.

3. Data Analysis and Results

The adopted methodology for analysing the data in this research is based on the use of Weighted Linear Combination (WLC). WLC is a technique of Multi-Criteria Evaluation (MCE) which is based on overlaying layers based on factors weights, factors ratings and/or constraints to create a suitability map [18]. The WLC technique includes the followings steps ([19] [20] [21] [22]):

1. Giving the appropriate ratings for each layer (vector format),
2. Converting all layers into raster format,
3. Multiplying maps weights by their ratings,
4. Combining all layers in order to have the overall suitability scores, and
5. Classifying the outcome into the required classes.

WLC within GIS enviornmnet has been adopted in several applications related to envionmental issues ([23]-[28]). Figure 5 illustrates the adopted methodology for analyzing the GIS data to calculate the final SWSi.

Table 5 summarizes the score values for each factor used to calculate the overall scores for the SWSi. It appears from this table that:

1. The highest scores for the Slope factor (24 and 30) have a small area (5.7%) of the total study area, while the smallest scores (6 and 12) cover 66.6% of the study area. This could be attributed to the fact that most of the study area is flat with a slope of less than 5%.

Table 3. SWSi ranges and classes.

Susceptibility Class	Low	Moderate	High	Very High
Susceptibility Range	21 - 42	42 - 63	63 - 84	84 - 105

Table 4. The data sets used in this research and their sources.

Map Type	Date	Scale/Resolution	Source
DEM	2000	1 arc-second (30 meter)	The Shuttle Radar Topography Mission (SRTM), USGS
Wadis	1995	1:250,000	Royal Jordanian Geographic Centre
Soil	1998	1:250,000	Jordan Ministry of Agriculture
Roads	2010	1:250,000	Royal Jordanian Geographic Centre
Urban	2016	1 m	Digitizing from Google Earth®/Digital Globe
Agriculture	2016	1 m	Digitizing from Google Earth®/Digital Globe

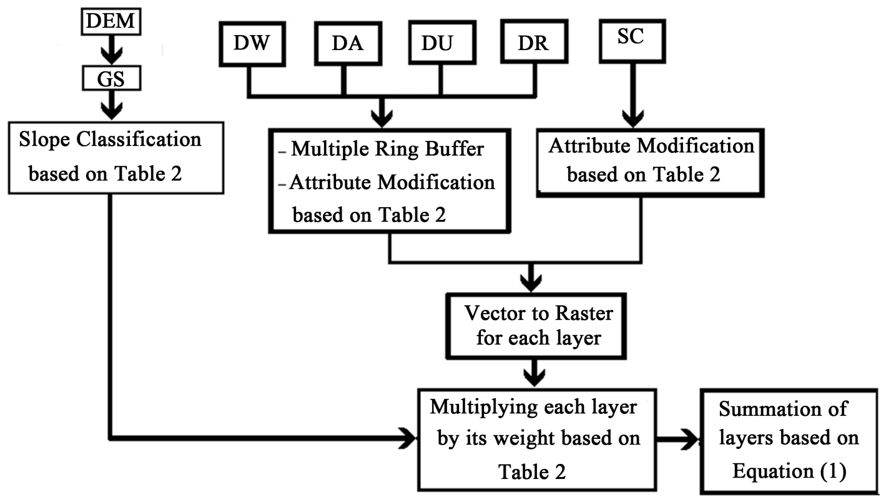

Figure 5. The adopted methodology for data analysis.

Table 5. Summary for the SWSi factors.

GS Scores	6	12	18	24	30
Area (km^2)	254.5	568.2	340.9	65.8	5.5
% of area	20.6	46	27.6	5.3	0.4
DW Scores	5	10	15	20	25
Area (km^2)	630.5	344.5	128.8	65.4	66
% of area	51	27.9	10.4	5.3	5.3
SC Scores	4	8	12	16	20
Area (km^2)	0	19.7	119.4	987.7	108.2
% of area	0	1.6	9.7	80	8.8
DA Scores	3	6	9	12	15
Area (km^2)	811.9	160.7	98.8	66.9	96.7
% of area	65.7	13	8	5.4	7.8
DU Scores	2	4	6	8	10
Area (km^2)	481.9	385	161.5	85.6	121
% of area	39	31.2	13.1	6.9	9.8
DR Scores	1	2	3	4	5
Area (km^2)	0.9	209.5	326.9	285.8	412
% of area	0.1	17	26.5	23.1	33.4

2. The highest scores for the Distance to Wadis (20 and 25) have a small area (10.6%) of the study area, while the smallest scores (5 and 10) cover (78.9%) of the study area.
3. The Soil (Clay%) factor highest scores (16 and 20) cover a large area (88.8%) of the study area, while the smallest scores (4 and 8) cover only 1.6% of the study area.
4. The distance to Agricultural Lands factor highest scores (12 and 15) cover (13.2%) of the study area, while the smallest scores (3 and 6) cover (78.7%) of

the study area. This could be attributed by the fact that most of the agricultural activities within the study area are located in the Western part of the study area.

5. The Distance to Urban Areas factor highest scores (8 and 10) cover (16.7%) of the study area, while the smallest scores (2 and 4) cover (70.2%) of the study area. This could be explained by the fact that most of the urban areas are concentrated in the Western part of the study area.
6. The Distance to Roads highest scores (4 and 5) cover an area (56.5%) of the study area, while the smallest scores (1 and 2) cover an area (17.1%) of the study area.

Figures 6-12 illustrate the factors (weight × ratings) used in this research to calculate the SWSi.

Based on Equation (1), the six factors shown in Figures 6-11 were summed using the raster calculator in ArcGIS® and then classified based on Table 2. Table 6 provides a summary for the final calculation of SWSi. It appears from this table that the low susceptibility areas has an area of 250 km^2 which comprises

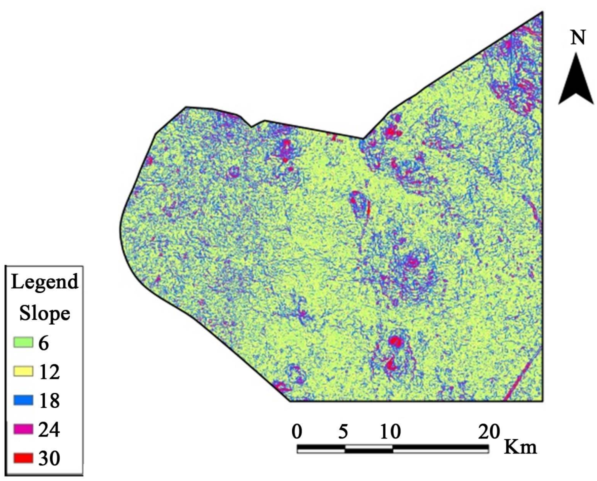

Figure 6. The slope factor.

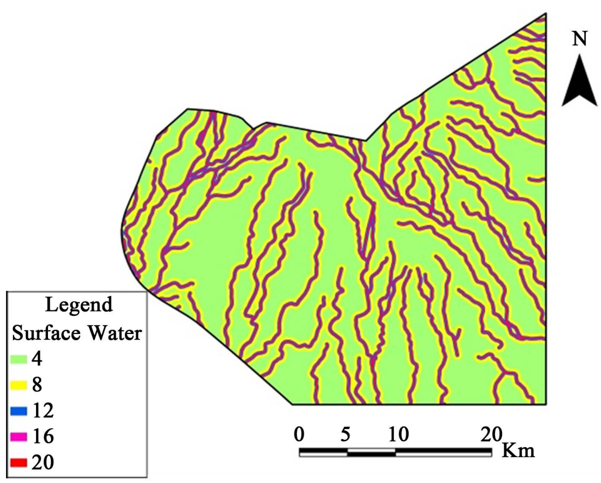

Figure 7. The distance to wadis factor.

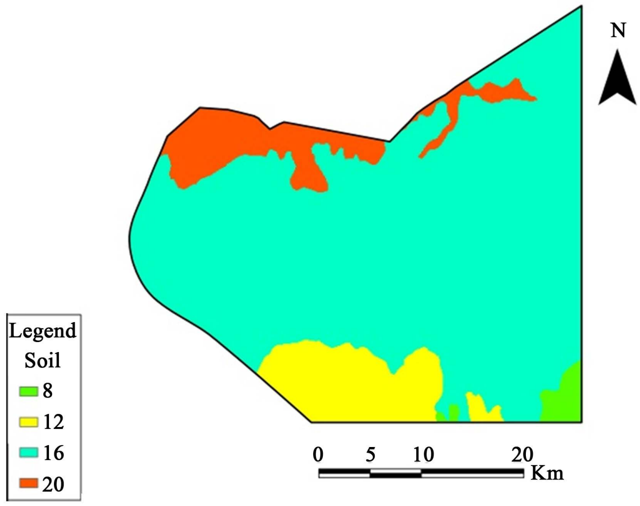

Figure 8. The soil (Clay%) factor.

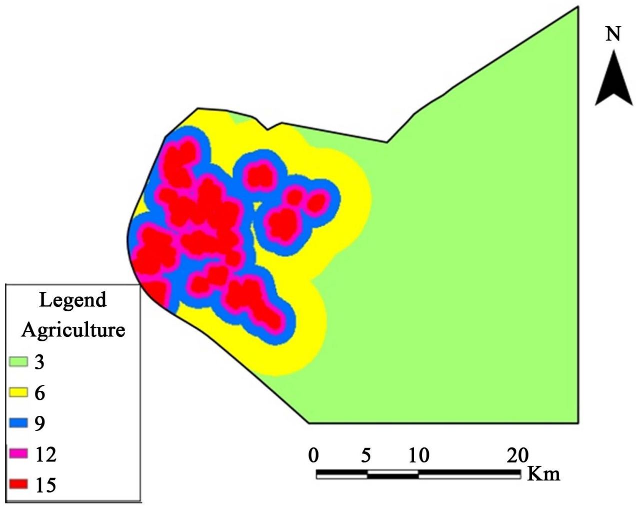

Figure 9. The distance to agricultural lands factor.

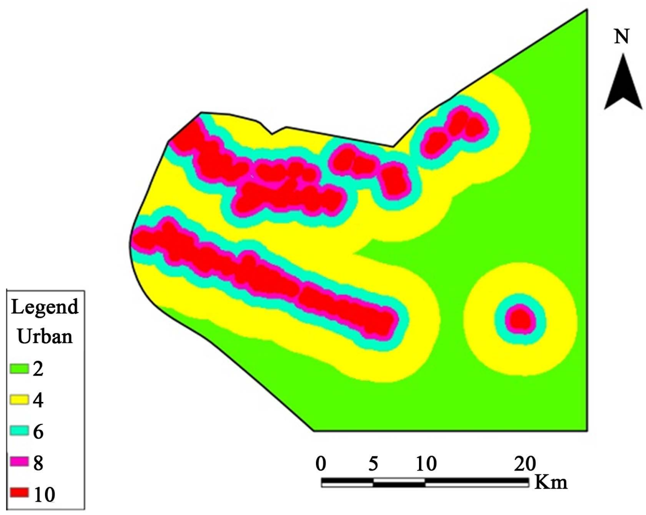

Figure 10. The distance to urban areas factor.

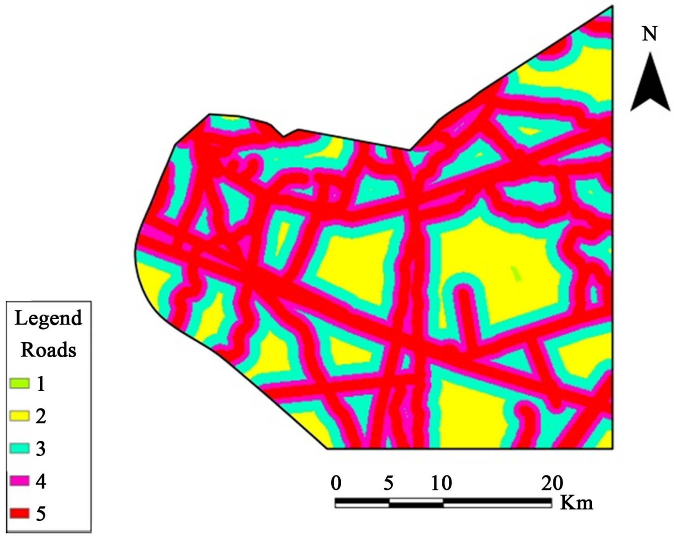

Figure 11. The distance to roads factor.

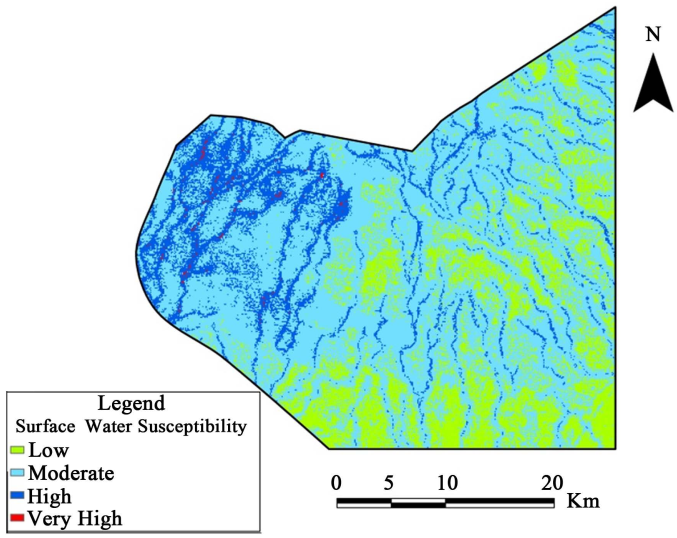

Figure 12. The final SWSi classes.

Table 6. A summary for the SWSi.

Class	Area (km^2)	% of total area
Low	250	20.2
Moderate	815.5	66.0
High	166.2	13.5
Very High	3.3	0.3
Total	1235	100

20.2% of the total study area. The areas with high and very high susceptibility have an area of 169.5 km^2 which comprises 13.8% of the study area. The remaining areas have a moderate susceptibility with a total area of 815.5 km^2 which comprises 66% of the total study area. Figure 12 illustrates the final classes of the SWSi. It shows that most of the very high and high susceptibility areas are located in the western part of the study area. This is in agreement with the existing urbanization and agricultural activities.

4. Sensitivity Analysis of the SWSi

4.1. Map Removal Analysis

Table 7 provides a summary statistics for the removal of one statistically significant factor on the SWSi values. This table indicates that the most important factors in the SWSi were DR, DU, DA and DW followed by GS and SC. The highest sensitivity value was associated with DR (47.9), while the lowest sensitivity value (35.8) was associated with SC.

4.2. Map Removal Sensitivity Analysis

Based on the map removal sensitivity analysis test developed by [29] and adopted by [30], which was used in this research to identify the sensitivity of each factor in the SWSy map. In this test, Equation (2) was used to calculate the sensitivity index (S) for the factors used in the vulnerability index.

$$S = \left|(V/N) - (V_{xi}/n)\right| \tag{2}$$

where: S is the sensitivity index of the factor;

V is the intrinsic vulnerability index of the method;

N is the total number of factors used to calculate V;

V_{xi} represents the intrinsic vulnerability index obtained after removal of the factor X and

n: the number of factors after removing one factor.

Based on Table 7 that lists the determined partial indices and Equation (2), the sensitivity index was calculated for each factor of the SWSi. Table 8 indicates that SC, GS and DR factors have a strong influence on the SWSi map, while DW, DA and DU factors have a moderate influences on the SWSi map.

5. Conclusions and Recommendations

In this research, 6 factors were used to estimate the Surface Water Susceptibility to pollution in a study area in Northern part of Jordan. These factors included slope, distance to Wadis, soil clay (%), distance to urban areas, distance to agri-

Table 7. The partial index calculated by removing one factor of the SWSi.

Factor Removed	Mean	Min	Max	SD
GS	38.5	20	75	8.86
DW	42.35	21	76	8.45
SC	35.8	18	80	9.65
DA	46.35	23	90	8.89
DU	47.3	24	90	9.23
DR	47.9	24	92	10.1

Table 8. Sensitivity index according to the map removal sensitivity analysis test for SWSi map.

Factors	Sensitivity Index			
	S Minimum	S Average	S Maximum	Standard Deviation (SD)
GS	0	1.03	5	0.83
DW	0	0.72	4	0.77
SC	0	1.43	3	0.58
DA	0	0.83	3	0.55
DU	0	0.89	3	0.58
DR	0	0.95	3	0.56

cultural lands and distance to roads. Each factor was given a weight appropriate to its importance in calculating the SWSi. Also, each factor was given the appropriate ratings at a scale 1 to 5, where 5 refers to the most susceptible area and 1 for the least susceptible area. The weighted linear combination (WLC) technique within GIS environment was used to calculate the overall score of the SWSi which then was classified into 4 classes (Low, Moderate, High and Very High susceptibility). The results showed that the low susceptible areas have a total area of 250 km^2 (20.2%). The very high and high susceptible areas have an area of 169.5 km^2 (13.8%), while the moderate susceptibility areas have an area of 815.5 km^2 (66%). The sensitivity analysis of the SWSi was carried out to determine the most significant factors. It was found that the most important factors in the SWSi were DR, DU, DA and DW. Also, the map removal sensitivity analysis was carried out to identify the sensitivity of each factor. It was found that SC, GS and DR factors have a strong influence on the SWSi map.

Based on these results, it is concluded that the major factors affecting surface water susceptibility to pollution are addressed in this index. Distances used for ratings urban, agriculture and roads are reasonable since these three factors are major contributors to surface water pollution. Contaminants flushed with rainfall when runoff is generated or passed one of these factors will degrade with distance. Based on that, it is recommended to use the SWSi to estimate surface water susceptibility to pollution. It is also recommended to look for other factors that might contribute to surface susceptibility to pollution. Furthermore, it's recommended to conduct a filed study in order to collect surface water samples at various distances from urban areas, agricultural lands and roads to investigate surface water quality. This might show the pollution of the surface water in reality to verify the outcomes of the SWSi and lead to the modification of given distances at this research.

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