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Developing a New Methodology for the Use of GIS and AHP in Determining Suitable Areas for Wheat Plants in the Lower Kelkit Basin

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ABSTRACT

In agricultural production planning; compiling the data correctly, and using and interpreting the data precisely have strategic importance. This study aims, it is aimed to develop a model that can evaluate the suitability of the Lower Kelkit Basin for wheat farming by using the Analytical Hierarchy Process (AHP) and current GIS technologies. In the study, weight values of seven different criteria of topography (slope, aspect) and soil (texture, organic matter (OM), $CaCO_3$, EC, pH) were calculated with AHP. These weight values and standardized criteria maps were combined within the ArcGIS Weighted Overlay tool and the result maps were created according to the FAO suitability index. According to these maps, 54% of the Lower Kelkit Basin was modeled as unsuitable (N) for wheat, 22% as moderately suitable (S2), and 24% as highly suitable (S1). In addition to all these, an editable and updatable ArcGIS model tool was also produced as a result of the study. Our results indicated that AHP and GIS are powerful and effective tools that can be used in land suitability modeling.

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Introduction

Agricultural land use assignment requires a land potential assessment as well as land demand for a large number of crops to identify the optimum land unit for each type. Available assignment models frequently approach the problem within the perspective of an increase in land demand. Nevertheless, actions causing the loss of arable land should be considered to correct the demand used in ordinary assignment operations (Pilehforooshha et al., 2014). For efficient and sustainable agriculture, crops must be grown in the most suitable areas for them. In recent years, GIS-based models have been used frequently in the determination and mapping of these kinds of areas. One of them is the analytical hierarchy process (AHP) developed by Thomas L. Saaty in the 1970s and being refined since then. Basically, AHP is a method for organizing and analyzing complex decisions using mathematics and psychology, and consists of three parts: (1) the problem to be solved (the ultimate goal), (2) all possible solutions called alternatives, and (3, 4) the criteria by which the alternatives will be evaluated (Shim, 1989). AHP has been widely applied for over 30 years to solve a wide variety of multi-criteria decision-making problems (Saaty, 1977; Saaty, 1980; Saaty and Vargas, 1991; Wu, 1998; Ohta et al., 2007; Chen et al., 2010, Chen et al., 2013). To succeed in AHP applications, the criteria to be used are important. Soil Properties (pH, Sand, Silt, Clay, EC, OM, $CaCO_3$), land use, land cover, elevation, slope, and aspect are important criteria that should be considered for modeling studies related to agriculture.

Today, it has become easier to access complementary data on these important criteria. For example, raster and vector maps related to Land Use and Land Cover prepared according to certain standards are offered to users from the official web addresses of the Environmental System Research Institute (ESRI) or the European Environment Agency (EEA). In this context, the Land use land cover (LULC) map by ESRI is available at https://livingatlas.arcgis.com/landcover/ and the Coordination of Information on the Environment (CORINE) database created for the purposes of the EEA is available to users at http://land.copernicus.eu/pan-european/corine-land-cover/clc2018. Elevation data is also provided as the ASTER Global Digital Elevation Model (ASTER GDEM) from NASA-EARTHDATA's official web address at https://earthdata.nasa.gov/search?q= ASTER+DEM. Slope and aspect raster maps can also be easily produced using the ASTER GDEM data and 3D functions of Arc/GIS software. Soil data can be accessed either from the websites of international organizations such as the International Soil Reference and Information Center (ISRIC) World Soil Information (Batjes et al., 2019) or by using available geo-referenced soil data collected from the field. It is possible to convert the geographically referenced soil data collected from the field into more detailed raster maps compared to global data sets by using spatial analysis methods (interpolation techniques) in Arc/GIS software. Furthermore, there is a suitability classification system developed by FAO regarding the requirements of important agricultural products such as wheat in terms of important soil variables (FAO, 1976).

The Lower Kelkit Basin is one of the basins that has been standing out in terms of agriculture and biodiversity both in Türkiye and the world. Because of these features, it is important to determine the most suitable areas for the products targeted to be grown in the basin with reliable and new methods. This study, it is aimed to present a new methodology by using AHP and GIS to determine the most suitable areas for organic wheat cultivation in the Lower Kelkit basin, and to present the suitability classes to the service of users by mapping them within this framework.

Materials and Methods

Study Area

Lower Kelkit Basin covers Almus, Başçiftlik, Erbaa, Niksar, Reşadiye districts of Tokat province and Taşova district of Amasya province. The basin's total area is 5597.45 km2 (Figure 1). The fact that the study area is in the transition zone between the Central Anatolia and the Middle Black Sea regions enables the climatic characteristics of both regions to be observed in the Lower Kelkit Basin. In addition, the geomorphology and topography of the land also have an impact on the climate of the region. While the Mediterranean climate is observed in the basin from the lower levels to 800 - 900 m altitude, as the altitude increases, the climate changes from west to east in the basin and continental climate characteristics begin to be seen (Doğan and Aslan, 2013).

Data Preparation and Standardization

In this study, spatial and non-spatial data sets were used for soil suitability modeling of wheat. The data sets and data sources used are briefly described in Table 1. Soil properties raster maps (Figure 2) were generated with ArcGIS 10.5 software using an archival Excel dataset from a soil analysis study carried out by Doğan and Aslan (2013). A soil texture raster map (Figure 2) was produced utilizing sand-clay-silt raster maps and the SAGA GIS software texture tool. Slope and aspect raster maps were derived from the spherical digital elevation model raster map (ASTER GDEM).

Basically, the digital elevation map was downloaded from the NASA-EARTHDATA website (EARTHDATA, 2020) as an ASTER GDEM with a spatial resolution of 30 m. Then, the workspace boundaries vector map was isolated from this raster elevation map by cutting (clip) the part falling into the study area using Arc/GIS software (ESRI, 2004). Slope and aspect raster maps of the study area were created by using this elevation raster map and Arc/GIS software (3D) functions (ESRI, 2004).

The Land use land cover (LULC) downloaded from the ESRI website (https://livingatlas.arcgis.com/landcover/) map was cut to cover the boundaries of the study area and prepared for analysis (Figure 3). Since each criteria map created has different values and measurement units, they have been standardized to analyze these maps. Except for the land use map, soil criteria maps have been standardized by classifying the soil requirements of wheat according to the FAO suitability classes (FAO, 1976). The corresponding FAO suitability classes of wheat soil requirements and their standard values are shown in Table 2. ArcGIS Reclassify tool was used to standardize the data.

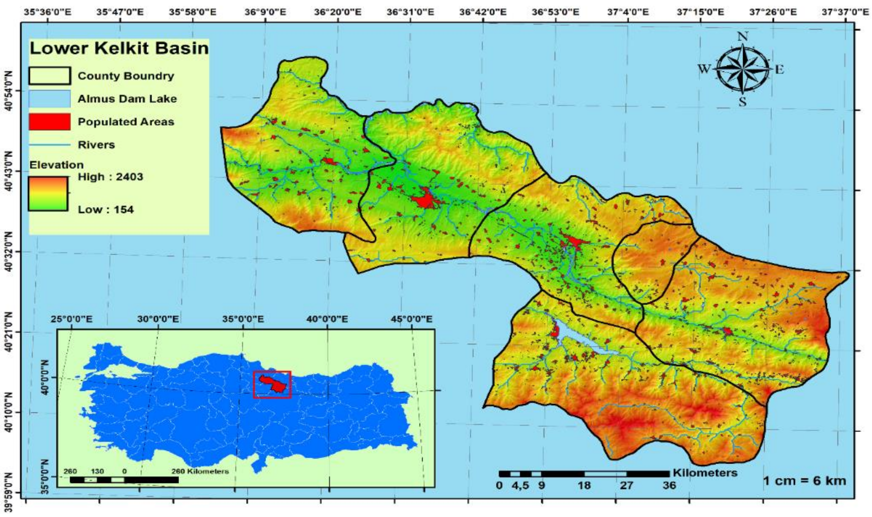

Figure 1. Study area districts, settlements and topographic features

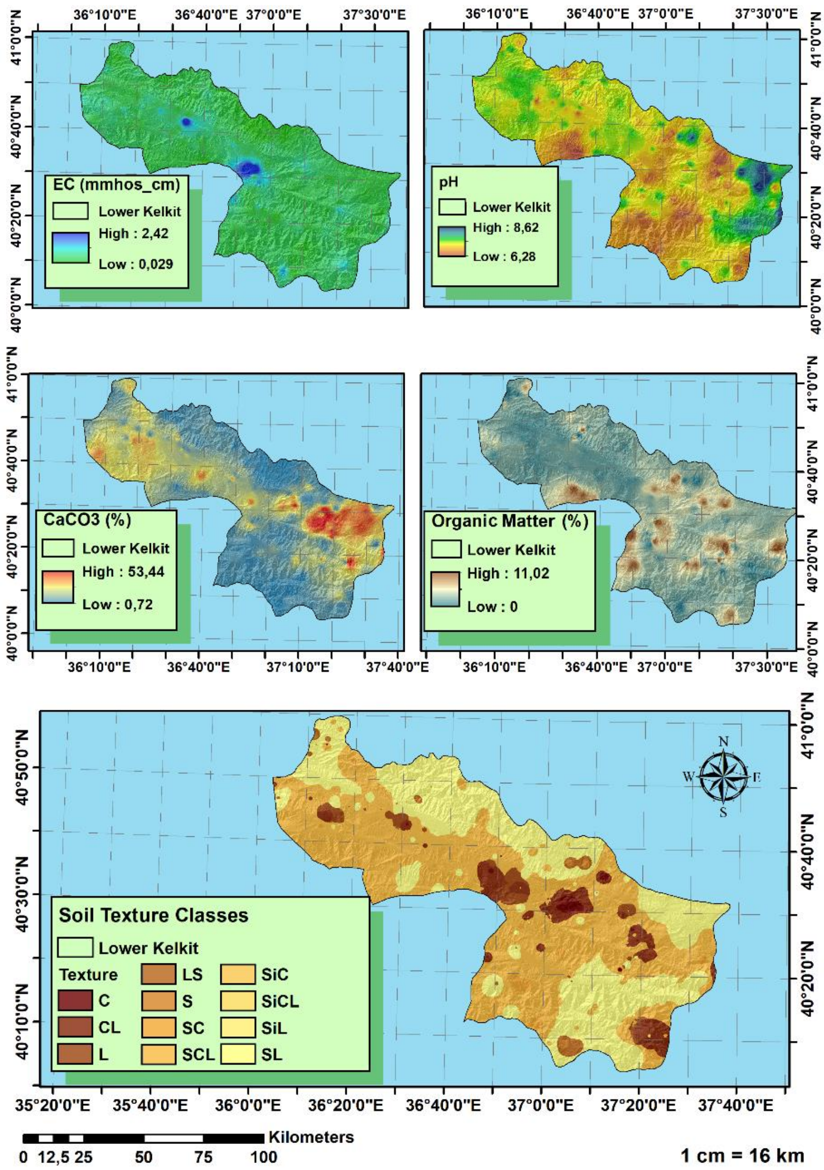

Figure 2. Lower Kelkit Basin soil properties raster maps (produced by archival data from Doğan and Aslan (2013) and texture map.

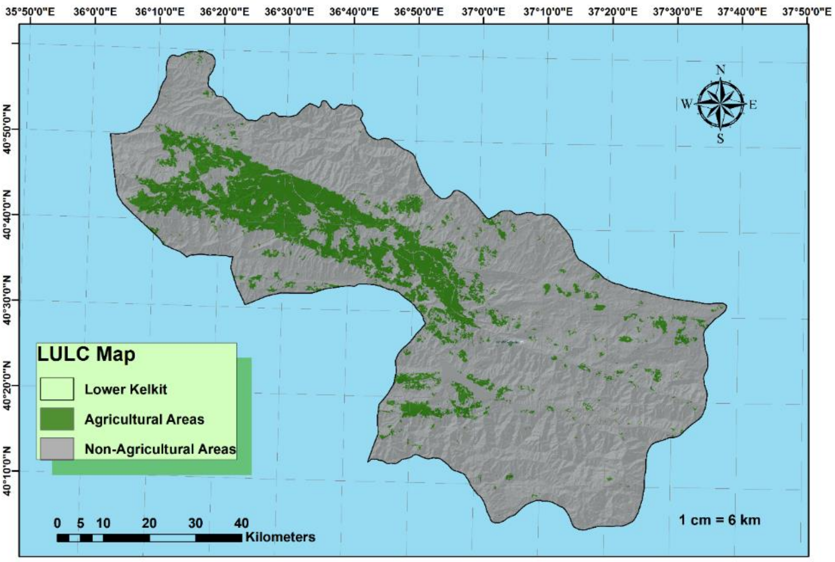

Figure 3. Land use land cover (LULC) map of study area

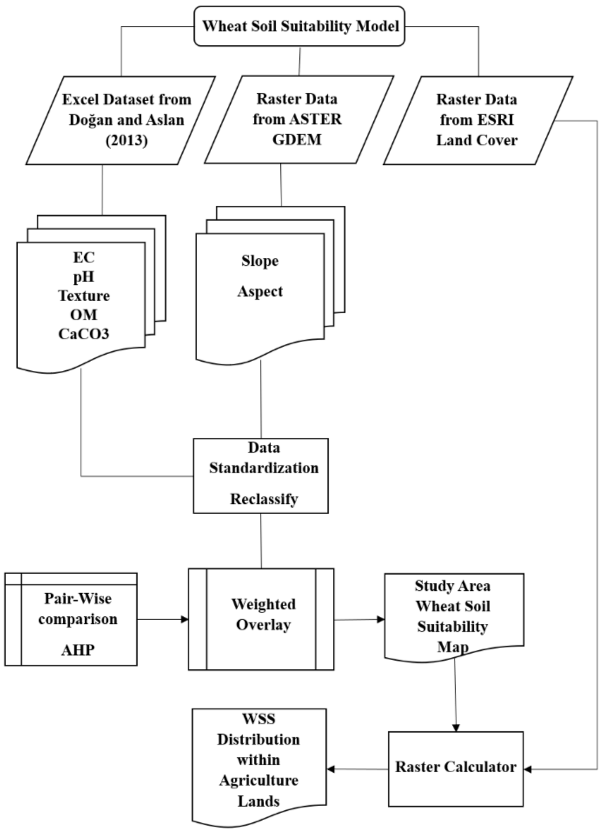

Figure 4. Flow chart of the methodology development

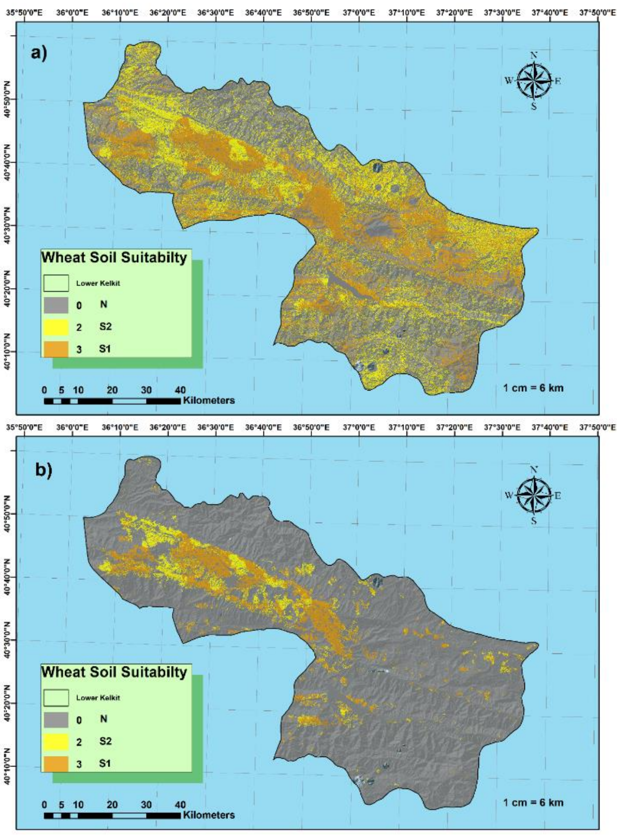

Figure 5. Wheat soil suitability maps in the study area. a) Wheat suitability distribution with non-agricultural areas. b) Wheat suitability distribution within the agricultural areas.

Multi-Criteria Weight Analysis Using AHP

Utilizing produced complementary data set (raster maps), a modeling process development for wheat soil suitability, shown step by step in the flowchart (Figure 4), was started. The weight values (Saaty, 2008) of each criterion selected for wheat soil suitability modeling were determined by the AHP algorithm. This algorithm is designed to evaluate the importance level of each criterion. In this process, each criterion undergoes an objective and subjective evaluation, and in the end, it is decided which criterion is the best option for the relevant subject. The process of determining the criterion weights takes place as explained below:

- In the first step, a pairwise comparison matrix is created based on a scale of 1 to 9 (Table 3), where 1 represents equal importance and 9 represents extreme importance between two criteria.
- In the second step, the weights/eigenvectors of the criteria are calculated.
- In the third step, the consistency of the matrix is calculated.

A consistency check is a powerful feature of AHP as a decision-making tool, allowing detection of potential errors by measuring the logical consistency of the matrix (Saaty, 1990; Mishra et al., 2015; Dedeoğlu and Dengiz, 2019). To calculate the Consistency Ratio (CR), the Consistency Index (CI) and the Random Index (RI) values should be known. The CI value is calculated according to Eq. 1.

$$CI=\frac{\lambda_{max}-n}{n-1} \quad (1)$$

In the equation, λ_{max} represents the maximum eigenvalue of the matrix, “n” represents the number of elements of the matrix. The Random Index (RI) value, unlike the CI value, is not calculated, but consists of constant values determined by Saaty (1977) for different matrix sizes (Table 4). After CI and RI values are obtained, CR is calculated according to Eq. 2.

$$CR=\frac{CI}{RI} \quad (2)$$

If the value calculated by equation 2 is less than 0.1, the matrix is considered consistent and the calculated weights are valid. Otherwise, the matrix needs to be rearranged. The consistency ratio calculated in this study is 0.098. Since this value is less than 0.1, the comparisons are valid (Saaty, 2008).

Table 5 shows the weight values and consistency ratio calculated in the comparison matrix, which consists of 7 criteria selected for the wheat soil suitability model. Comparison of criteria was carried out based on previous studies and literature on wheat soil requirements (Sys et al., 1993; Geçit et al., 2011; Zengin and Özbahçe, 2014; Dedeoğlu and Dengiz, 2019; Tashayo et al., 2020).

The soil Suitability Model for Wheat

The soil suitability model was produced using ArcGIS Model Builder. From standardizing data to generating the results map, Model Builder combines multiple analyzes in one operation. In this study, 3 analysis tools were used in the model builder: Reclassify for standardizing the data, Weighted

Overlay for combining the data according to the weight values was calculated with AHP, and finally Raster Calculator for the extraction of non-agricultural lands was used.

Results and Discussion

As a result of Weighted Overlay and Raster Calculator analyses, two suitability maps were produced for wheat: a) Wheat Suitability map for total study area and b) Wheat suitability classification map according to agricultural lands (Figure 5). According to the ESRI land use map, the total study area was calculated as 580944 hectares. While 17% (99129 ha) of this calculated area is agricultural lands, 83% (481815 ha) is non-agricultural lands. In the wheat soil suitability map for total study area created after the Weighted Overlay analysis, the suitability values were distributed as unsuitable (313695 ha), high (S1) (135324 ha), and moderate (S2) (129326 ha), respectively. However, there are non-agricultural areas among these calculated areas. For this reason, non-agricultural areas were extracted using the ESRI Land Cover map and the area distribution was calculated again. As a result of this calculation, 48% (47581,92 ha) of the agricultural land areas were found highly suitable (3/S1) for wheat crop. However, 27% (26764,83 ha) and %25 (24782,25 ha) of the agricultural land areas were found moderately suitable (2/S2), and unsuitable (0/N), respectively.

In this study, it has been shown that wheat land suitability can be evaluated practically by using AHP and GIS together. The weights of seven selected parameters of topography (slope, aspect) and soil (texture, OM, $CaCO_3$, EC, pH) were calculated using AHP and successfully modeled with GIS. According to the suitability map produced, 54% (N) of the entire basin was unsuitable for wheat, while 22% (S2) and 24% (S1) were classified as suitable for wheat.

Table 1. Utilized available datasets in the study.

Data Sets	Data Type	Source
Soil Properties (pH, Sand, Silt, Clay, EC, OM, $CaCO_3$)	Excel Data Set from Lab. Analysis	Doğan and Aslan (2013)
Slope and Aspect	Raster	ASTER Global Digital Elevation Model (ASTER GDEM) https://asterweb.jpl.nasa.gov/gdem.asp
Land use land cover (LULC) map	Raster	ESRI Land Cover https://livingatlas.arcgis.com/landcover/

Table 2. Wheat soil requirements sub-criteria, corresponding FAO classes (FAO, 1976) and standard values.

Soil Requirements for Wheat							FAO Suitability	Standard Values
EC	Slope	Texture	OM	pH	Aspect	$CaCO_3$		
0-3	0 - 4	SiC, L, CL	> 2.5-1,5	6 – 8.2	S, SW, SE	3-30	S1 (High)	3
3-5	4 - 8	SCL	1.5-1	8.2 – 8.3	E, W	30-40	S2 (Moderate)	2
5-6	8 - 16	SL	<1	8.3 – 8.5	NE, NW	40-60	S3 (Marginal)	1
6<	16 <	-	-	<6-8,5<	N	60<	N (Not suitable)	0

Table 3. The ratio scale and definition of AHP (Saaty, 1990).

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values

Table 4. RI values for different matrix sizes (Saaty, 1977).

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.53	1.56	1.57	1.59

Table 5. AHP Matrix and CR value.

Criteria	EC	Slope	Texture	OM	PH	Aspect	$CaCO_3$	Weights
EC	1,00	0.33	2.00	0.33	2.00	2.00	2.00	0.13
Slope		1,00	0.33	0.33	3.00	3.00	3.00	0.18
Texture			1,00	0.33	1.00	2.00	2.00	0.14
OM				1,00	3.00	4.00	5.00	0.32
PH					1,00	3.00	3.00	0.11
Aspect						1,00	2.00	0.07
$CaCO_3$							1,00	0.05
CR Value	0,098							

The criterion weights calculated with AHP are in agreement with the weights obtained in different studies (Dedeoğlu and Dengiz, 2019; Tashayo et al., 2020; Kılıç et al., 2021) in which wheat land suitability was determined. As in the studies carried out; In this study, slope, pH, texture and EC criteria were highly influential criteria in wheat land suitability assessment.

In addition, when comparing the criteria, special cases for the study areas should be taken into account. According to Dedeoğlu and Cengiz (2019) and Kılıç et al. (2021) who worked at high altitudes, soil depth is important when compared with other criteria.

According to Tashayo et al. (2020), texture was the most important criterion if the soils of the study area had high lime content. Since the data of our study is based on a research based on organic agriculture, the most important soil criterion was determined as soil organic matter.

The distribution of soil texture, OM, pH, $CaCO_3$ and EC values in the range of values that do not limit the growth of wheat and provide optimum conditions in the study area has been effective in modeling the suitability of the land (especially S1and S2 classes) for wheat cultivation. However, the slope criterion, which takes the second most important weight value in the AHP analysis, has been the determining factor in calculating the unsuitable areas for wheat in the study area by limiting the suitability distribution.

Considering the negative effects of the slope such as making agricultural mechanization processes such as planting, harvesting and irrigation difficult and increasing the risk of erosion (Fao 1977, Dedeoğlu and Dengiz, 2019; Tashayo et al., 2020); Classification of areas with high slope grades as unsuitable for wheat cultivation is necessary for a functional land suitability model. The model produced in the study successfully made this determination.

Another functional feature of the model produced in the study is that it is prepared using ArcGIS Model Builder, so it allows updating and making changes on it. For example, it has been reported that one of the important soil criteria for wheat production is sufficient soil depth (Sys et al., 1993; Zengin and Özbahçe, 2014; Dedeoğlu and Dengiz, 2019). Since there is no soil depth data set belonging to our study area, it could not be included in the model. However, this lack of data set will not hurt our model in the long run. Because our model is open to editing; When new datasets related to the study area, such as soil depth, are obtained, they can be easily added to the model.

In this study, it has been shown that AHP and current GIS technologies are powerful tools that enable the production of functional models for complex agricultural planning by processing large amounts of heterogeneous data. Thanks to these tools, both the general wheat suitability potential of the Lower Kelkit Basin and the wheat suitability potential within the agricultural areas of the basin were successfully modeled and mapped.

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Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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