

PAPER • OPEN ACCESS

## Marvellous “1” : A Spatio-temporal Model of Ecological Environment

To cite this article: Zhilin Huang *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **295** 012087

View the [article online](#) for updates and enhancements.

# Marvellous “ 1 ” : A Spatio-temporal Model of Ecological Environment

Zhilin Huang<sup>1,a</sup>, Shanshan Jiang<sup>2,b</sup>, Xin Wang<sup>3,c</sup>, Yujie Zhang<sup>\*4,d</sup>

<sup>1</sup>School of Light Industry and Chemical Engineering, Dalian Polytechnic University

<sup>2</sup>School of Biological Engineering, Dalian Polytechnic University

<sup>3</sup>School of Textile and Material Engineering, Dalian Polytechnic University

<sup>4</sup> School of Information Science and Engineering, Dalian Polytechnic University, Dalian, 116034, China

<sup>a</sup>Email: 854436282@qq.com; <sup>b</sup> Email: 1445506827@qq.com; <sup>c</sup> Email: 3437497519@qq.com;

<sup>d</sup>Email: zhangyj@dlpu.edu.cn; Yujie Zhang\*, Corresponding Author, Associate Professor

**Abstract:** Traditionally, most land-use projects do not take the impact of ecological degradation into account. The negative economic costs of land use change are substantial. To tackle these problems, in this paper, we established a spatio-temporal ecological environment model.

First, we select the method of Principal Component Analysis (PCA) to screen out the tertiary time-related indicators which affect ecological environment, then adopt Weighted Average Algorithm (WAA) to calculate the weights of the secondary indicators. Meanwhile, make each feature quantity at the same level and get their weighted sum. When the exploitation of ecological resources is balanced with its carrying capacity, the weighted sum is tend to 1.

Then we find the spatial variable, and introduce the ratio of supply and demand, which named supply-demand coefficient, and make up an equation with the weighted sum mentioned above. When the supply and demand of a region are balanced, the supply-demand coefficient mentioned above is equal to the weighted sum, which is also 1. When the supply is greater than the demand, both sides of the equation are greater than 1, at this time, excessive supply causes unnecessary economic costs.

Finally, we use the Genetic Algorithm (GA) to evaluate the supply-demand coefficient, so as to adjust the environmental degradation caused by land development projects in time.

## 1. Introduction

Many natural processes are continually supplied by the biosphere to maintain a healthy and sustainable environment for human life, which are known as ecosystem services [1]. Despite growing awareness of impacts that land use change has on the environment, a large body of small projects and large-scale projects are still being implemented, which seems insignificant to the biosphere, but for a long period of accumulation, they are directly causing environmental degradation. Consequently, with an attempt to deal with these problems, creating a land management strategy and an ecological services valuation model to determine the best ecosystem supply and reduce unnecessary ecological costs is eager to be carried out.



## 2. The Time-Related Ecological Environment Model

The economic costs of land use projects can be measured by the supply of freshwater, food and fuel provision, flood regulation and soil erosion macro-monitoring[2]. These factors may be influenced by time factors such as seasons.

### 2.1 The Supply of Freshwater

We define  $W_t$  as a coefficient, which means the product of water quality and quantity[3], the  $W_t$  is calculated with following equation:

$$W_t = \overline{W_y} / \overline{W_r} \times \overline{WQ_t} \quad (1)$$

Where  $\overline{W_y} / \overline{W_r}$  is the quotient of water yield ( $m^3/s$ ) and the water requirement over a period of time ( $m^3/s$ ), that is the quantity of water.  $\overline{WQ_t}$  is the weighted sum of the concentrations of substances that affect the quality of water. The standard value of  $W_t$  should be 1. When one of them exceeds the standard or fails to meet the standard,  $W_t$  deviates from 1.

### 2.2 Food and Fuel Provision

Let  $F$  denote the food provision index, and  $F_q$  denote the food provision quantity, the formulas can be expressed by the following equation:

$$F = \frac{F_q}{\sum_{i=1}^n T_i} \quad (2)$$

Where  $\sum_{i=1}^n T_i$  is the weighted sum of various grain requirements, when the grain yield in a certain period reaches the demand in this time range, the value of  $F$  is 1, otherwise it's going to be greater than or less than 1.

Similarly, we define  $F_u$  as the fuel provision index[4], and  $F_{u_q}$  as the fuel provision quantity, which are shown as below:

$$F_u = \frac{F_{u_q}}{\sum_{i=1}^n T_{u_i}} \quad (3)$$

Where  $\sum_{i=1}^n T_{u_i}$  is a weighted value of the amount of fuel required over a period of time, during this period, when the fuel production reaches the required quantity,  $F_u$  is 1, and in the case of oversupply,  $F_u$  is greater than 1, otherwise less than 1.

### 2.3 Soil Erosion Macro-monitoring

Human activities tend to break the original state of natural balance of land erosion rate[5]. Let  $E_t$  represent the erosion indicator, which can be expressed by the following equation:

$$E_t = \exp^{((E_a/E_{\max})-1)} \quad (4)$$

Where  $E_a$  denotes the erosion rate during a period of time, and  $E_{\max}$  is the maximum tolerable rate of erosion.  $E_a/E_{\max}$  is equal to 1 when the soil erosion rate is equal to the allowable value.  $(E_a/E_{\max} - 1)$  is equal to 0, and the exponential function with base  $e$  is equal to 1 when its exponent is equal to 0. In other words, when the function value  $E_t$  is less than or approaching 1, it indicates that soil and water conservation is good. Otherwise, the land will be excessively eroded.

### 2.4 Flood Regulation

Over time, human activities, such as population increase and land development, can dramatically change flood conditions.

To quantify the flood index[6][7],we define three indexes construct the equation:

$$Fl = w_1 \times (D_t/D_i) + w_2 \times (S_t/S_i) + w_3 \times (N_t/N_i) \quad (5)$$

Where  $w_i$  are the weights for each component,  $D_t$ ,  $S_t$  and  $N_t$  are respectively the duration of flood disaster, the scale of flood disaster and the number of flood disaster in a period of time;  $D_i$ ,  $S_i$  and  $N_i$  are their maximum allowable values, respectively.

### 3. Ecological Services Valuation Models

In the previous section, we proposed five quantitative indicators, to make all features in the same level, we need feature scaling, or data scoping, because these characteristic quantities all have a wide range of values. If we don't process the values, the model will be dominated by one of these factors. In our model, we adopt Weighted Average Algorithm[8](WAA) to scaling the range of features in the range of [0,1].

The general formulas are like these:

$$WAA_w(a_1, a_2, \dots, a_n) = \sum_{k=1}^n w_k a_k \quad (6)$$

Where  $w = (w_1, w_2, \dots, w_n)^T$  is the weight vector of the data array  $(a_1, a_2, \dots, a_n)$ , and  $w_k \in [0,1]$ ,  $1 \leq k \leq n$ ,  $\sum_{k=1}^n w_k = 1$ .

This problem needs to calculate the weighted sum of five indicators, so the value of  $k$  is from 1 to 5.

Prior to using the formula above, we need gather abundant data and filter them preliminarily. We will take Lake havasu, Arizona as an example to illustrate our normalization method.

To screen out the main influencing factors from a large number of indicators and simplify the problem, with the help of the software, we extracted the valid data. The extraction method of data is based on Principal Component Analysis(PCA).

From the data output by SPSS software shown in Table 1 and 2, the quantitative value of total variance explanation and *component matrix*<sup>2</sup> can be obtained.

Table 1.Total Variance Explained

Total Variance Explained						
Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.350	39.159	39.159	2.350	39.159	39.159
2	2.062	34.373	73.531	2.062	34.373	73.531
3	.701	11.688	85.219			
4	.506	8.439	93.658			
5	.316	5.261	98.920			
6	.065	1.080	100.000			

Extraction Method: Principal Component Analysis.

Table 2.Component Matrix<sup>a</sup>

<b>Component Matrix<sup>a</sup></b>		
	Component	
	1	2
AVG ELEVATION	-.108	-.757
AVG CONTENT	-.720	.264
AVG INFLOW	-.035	.820
AVG OUTFLOW	.186	.865
AVG HIGH TEMP	.930	.001
AVG LOW TEMP	.958	-.026
Extraction Method: Principal Component Analysis.		
a. 2 components extracted.		

As is shown in Table 1 ,we select the indicators with a higher cumulative percentage (the first two items). Two principal components were scored with six tertiary indicators in table 2 that affect the fresh water supply, and the scores of these two principal components were recorded with  $S_j$ , it can be expressed as:

$$S_j = \sum_i^n \lambda_i ZX_i, \quad i = 1, 2, \dots, 6 \quad (7)$$

Because the dimensions of the six indicators are different, we use the following equation to normalize the coefficient  $\lambda_i$  corresponding to the index score:

$$\lambda_i = \frac{PEC}{\sqrt{TIE}}, \quad i = 1, 2, \dots, 6 \quad (8)$$

Where:

- PEC=the principal eigenvalues of the six indicators
- TIE=the total initial eigenvalues

Table 3. The coefficient  $\lambda_i$  of each principal component

	$\lambda_1$	$\lambda_2$	$\lambda_3$	$\lambda_4$	$\lambda_5$	$\lambda_6$
principal component 1	-0.068	-0.453	-0.022	0.117	0.585	0.602
principal component 2	-0.499	0.174	0.541	0.570	-0.001	-0.017

$ZX_i$  is the normalized value of the original variable. Comparing these indicators, they can be classified as three types, Income-Type Indicator, Cost-Type Indicator and Stability-Type Indicator[9]. Due to the different contribution of the indicators, the three types of indicators are standardized in different ways as follows.

• **Income-Type Indicator**

In this type,  $ZX_i$  is positively with  $X_i$ .

$$ZX_i = \frac{X_i - X_i^{\min}}{X_i^{\max} - X_i^{\min}}, \quad i = 1, 2, \dots, 6 \quad (9)$$

Where  $X_i^{\max}$  is the largest index of  $X_i$ ,  $X_i^{\min}$  is the smallest index of  $X_i$ .

• **Cost-Type Indicator**

In this type,  $ZX_i$  is negatively with  $X_i$ .

$$ZX_i = \frac{X_i^{\max} - X_i}{X_i^{\max} - X_i^{\min}}, \quad i = 1, 2, \dots, 6 \quad (10)$$

• **Stability-Type Indicator**

$$ZX_i = \frac{X_i}{X_{\max}}, \quad i = 1, 2, \dots, 6 \quad (11)$$

Where  $X_{\max}$  is the maximum index of the  $X_i$

Combining with the formula given above, we get the value from  $ZX_1$  to  $ZX_6$  easily. Their values can be represented in the following table:

Table 4. The value from  $ZX_1$  to  $ZX_6$

$ZX_1$	$ZX_1$	$ZX_1$	$ZX_1$	$ZX_1$	$ZX_1$
-0.71	-0.56	1.02	1.78	0.87	0.39
-0.58	-0.89	1.38	1.62	0.76	0.75

The total score of the  $j$ th component,  $S_j$ , can be given by:

$$S_1 = -0.068 \times (-0.71) - 0.453 \times (-0.56) - 0.022 \times (1.02) + 0.117 \times (1.78) + 0.585 \times (0.87) + 0.602 \times (0.39) \approx 1.03 \quad (12)$$

$$S_2 = -0.499 \times (-0.58) + 0.174 \times (-0.89) + 0.541 \times (1.38) + 0.570 \times (1.62) - 0.001 \times (0.76) - 0.017 \times (0.75) \approx 1.72 \quad (13)$$

The weighted scores of the two main indicators can be expressed as:

$$S = \sum_{j=1}^n \left( \frac{PV}{CP} \times S_j \right), \quad j = 1, 2 \quad (14)$$

Where:

- PV=the percentage of variance
- CP=the cumulative percentage

$$S = \frac{36.046}{68.897} \times 1.03 + \frac{32.851}{68.897} \times 1.72 \approx 1.36 \quad (15)$$

The score of freshwater supply can be obtained from the above calculation, and the score is about 1.36, with the same method, a conclusion can be drawn that the score of food and fuel provision, soil erosion macro-monitoring and flood regulation are 0.78, 0.56, 1.38 and 1.13.

The total score of secondary indicators  $w_{sum}$  is:

$$w_{sum} = 1.36 + 0.78 + 0.56 + 1.38 + 1.13 = 5.21 \quad (16)$$

Table 5. The weight calculation results corresponding to each factor

Factors	Weight
Freshwater supply	$w_1 = 1.36/w_{sum} = 0.261$
Food provision	$w_2 = 0.78/w_{sum} = 0.150$

Fuel provision	$w_3 = 0.56/w_{sum} = 0.107$
Soil erosion macro-monitoring	$w_4 = 1.38/w_{sum} = 0.265$
Flood regulation	$w_5 = 1.13/w_{sum} = 0.217$

The specific weights are as follows

$$w = [0.261 \quad 0.150 \quad 0.107 \quad 0.265 \quad 0.217] \quad (17)$$

#### 4. Assess Environmental Costs Using State-Time Models

After grasping the models of natural ecosystems quantification and the weight of each indicator, we can have a detailed analysis about environmental cost.

The five influencing factors of the quantitative indicators share a common core: when the indicators are in a stable state, their values are 1. When their values are not 1, the environmental supply or human activity consumption is abnormal.

Furthermore, since the total cumulative value of the weight is 1, assuming a simple additive relationship between the five indicators, the comprehensive value of each indicator should be 1 when the environment is under ideal condition:

$$W_t \times w_1 + F \times w_2 + Fu \times w_3 + E_t \times w_4 + Fl \times w_5 = 1 \quad (18)$$

In addition, as we all know, when human beings take resources on demand without excessive reclamation, in other words, when the ratio of supply to demand is 1, the natural environment will tend to be stable in time. The equation can be expressed as:

$$\varepsilon = \frac{\text{supply}}{\text{demand}} = 1 \quad (19)$$

Therefore, we deduce the time-space relationship that affects the ecological environment as follow

$$\varepsilon = W_t \times w_1 + F \times w_2 + Fu \times w_3 + E_t \times w_4 + Fl \times w_5 \quad (20)$$

Where we define  $\varepsilon$  as a coefficient of supply and demand, which could be treated as the ratio of what is available to what is needed. It will be explained in detail in the next section.

#### 5. Supply and Demand Coefficient $\varepsilon$ and Environmental Cost

Take the supply of fresh water as an example, if the quotient of water consumption and population exceeds the average water demand or the number of people is not directly proportional to the amount of water use, a region can be defined as water shortage. In other words, when the demand for fresh water exceeds the average supply, the region is defined as short of water.

The chart below shows the relationship between population and water use in California's 10 most populous cities:

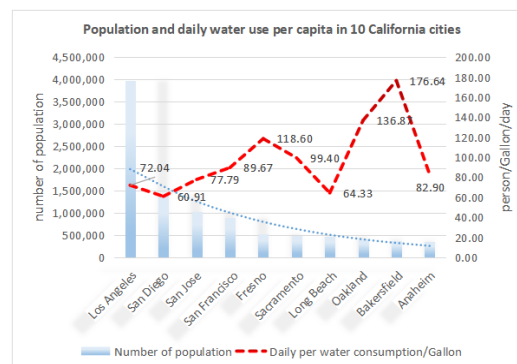


Figure 1. Population and daily water use per capita in 10 California cities

For fresh water supply and demand coefficient[10]:

$$\varepsilon = \frac{WIC/\overline{Wu}_{10}}{Ap/\overline{P}_{10}} \quad (21)$$

Where

- $WIC$  is the water consumption per capita in each city
- $\overline{Wu}_{10}$  is the water consumption per capita in ten California cities
- $Ap$  is the average population of a city
- $\overline{P}_{10}$  is the average population of ten cities in California.

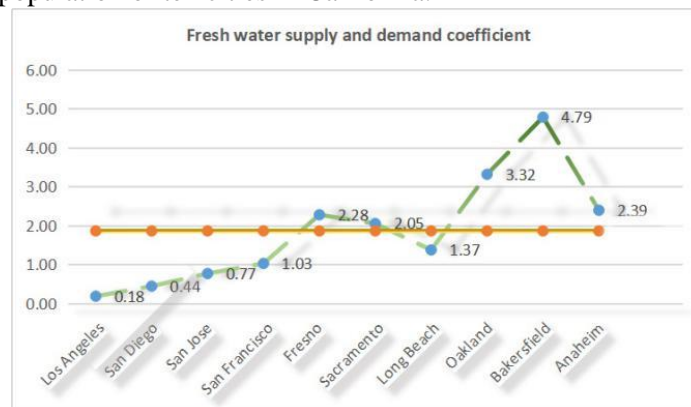


Figure 2. Fresh water supply and demand coefficient

The specific analysis associated with the diagram is that the value of supply and demand coefficient from Los Angeles to San Francisco are less than or approximately 1, but from Fresno to Anaheim are far more than 1. The orange line represents the mean of the coefficients  $\varepsilon$ , which is 1.86.

The above method can also obtain the mean of the supply and demand coefficient  $\varepsilon$  of other land use projects, which can be expressed by radar chart:

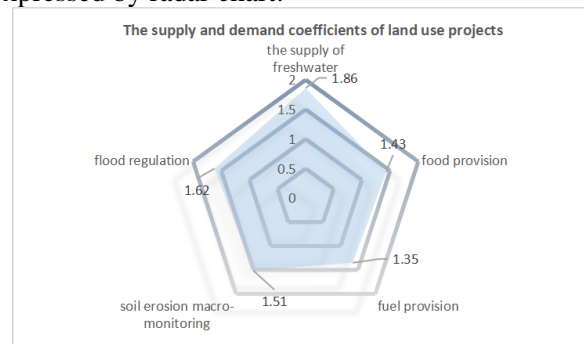


Figure 3. The supply and demand coefficient of land use projects

As the environmental cost of land development project is directly affected by it,  $\varepsilon$ 's value greater than 1 indicates that the supply is greater than the demand, and the larger the value of  $\varepsilon$ , the higher the unnecessary negative cost of land development is.

These results suggest that the environmental costs of California's land-use development projects exceed the state's own needs, and that Overexploitation could lead to environmental degradation.

## 6. The Relationship Between Environmental Degradation and Project Costs

Any variation of one of the factors mentioned in Section 2. may lead to change in the environmental costs of land development projects. Therefore, in the following analysis, we use Genetic Algorithms[11](GA) to simulate the changes in the environmental costs of land development projects in California in the coming decades.



According to the idea that the probability of each factor being selected in environmental degradation is proportional to its fitness, we calculate the probability of each factor.

First, we calculate the fitness of each individual in the population, in our models, the fitness is  $\varepsilon_k$ , then find the probability that each individual will be passed on to the next generation:

$$P_k = \frac{\varepsilon_k \times w_k}{\varepsilon}, \quad k = 1, 2, \dots, 5 \quad (22)$$

The sum of these probabilities is:

$$q_k = \sum_{k=1}^5 P_k = 1 \quad (23)$$

The probability of each factor being selected in the process of environmental degradation is as follow:

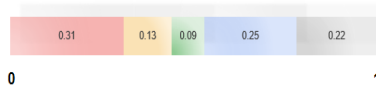


Figure 4. The probability of each factor being selected in the process of environmental degradation

Produce a uniformly distributed pseudo-random number  $r$  within  $[0,1]$ , if  $r < q_1$ , select the individual 1, otherwise, select the individual  $k$ , make  $q_{k-1} < r \leq q_k$ . Repeat the above steps 5 times.

Matlab substitution of the above values, generate the following function image, and the conclusion is that the stable value of  $\varepsilon$  is about 1.9465.

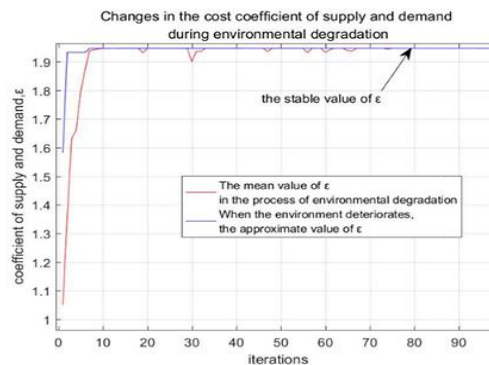


Figure 5. Changes in the cost coefficient of supply and demand during environmental degradation

## 7. The Change Rule of the Model with Time and Space

As mentioned above, our model can be represented by the following time-space equation. Where, the left side of the equation is the spatial model, which means the ratio of resource supply and demand within a certain region, represented by the coefficient  $\varepsilon$ , while the right side of the equation is the time model, and each index is a function of time.

If we want to perform a cost benefit analysis of land use development projects from community to country, we just need to find the respective supply-demand's affecting factors of five indicators, which are the supply of fresh water, food and fuel supplies, land erosion protection, flood protection in different spatial scope, or in different regions, then take a weighted operation for them.

We gather abundant data and perform a cost benefit analysis, the results are shown below:

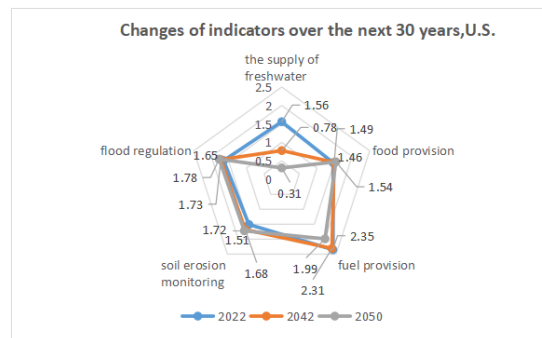


Figure 6. Changes of indicators over the next 30 years,U.S.

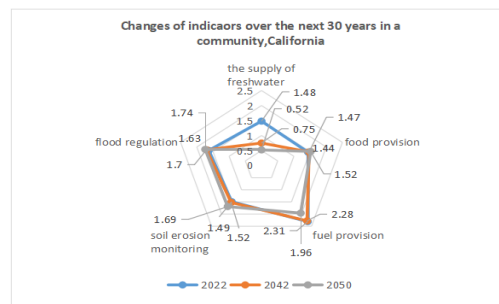


Figure 7. Changes of indicators over the next 30 years in a community,California

As can be seen from figure 6 and figure 7, whether the United States or a community, water and fuel resources will be in short supply in the coming decades, while the cost of water and soil conservation, flood control and food supply are still at high levels, but ecological services will also incur unnecessary negative costs.

Table 6. The change of coefficients from community to country

year \ $\varepsilon$	$\varepsilon_{U.S.}$	$\varepsilon_c$
2022	1.64	1.60
2042	1.49	1.43
2050	1.36	1.40

From the table given above, the coefficients of supply and demand,  $\varepsilon$ , from the country to the community show a downward trend. On the one hand, it indicates that the supply and demand relationship tends to be stable; on the other hand, it indicates that the cost of land use and development projects has been effectively controlled.

## 8. Sensitivity Analysis

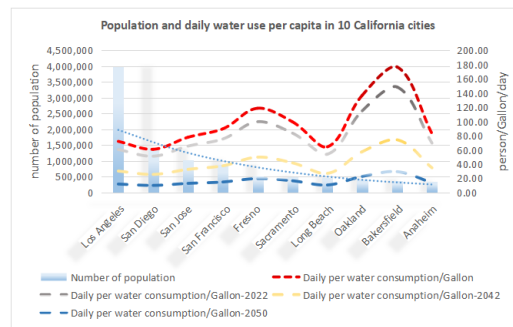


Figure 8. The predict of population and daily water use per capita in 10 California cities from 2022 to 2050

As shown in the figure, we take the water resource supply in the next 30 years as an example and conduct sensitivity analysis. The results show that the balance of water resource supply and demand in 2042 is conducive to reducing unnecessary ecological expenditure and avoiding environmental degradation, while in 2050, there may be a problem of insufficient water resource supply, which needs timely adjustment. Other indicators can be predicted and analyzed by the same method, and the sensitivity of the model is favorable.

## References

- [1] Xie, H., Wang, J., & Hu, J. (2012). Environmental Impact Assessment of Land Use Planning Based on Ecosystem Services Valuation in Xingguo County. *Procedia Environmental Sciences*, 12, 87-92.
- [2] Logsdon, R. A., & Chaubey, I. (2013). A quantitative approach to evaluating ecosystem services. *Ecological Modelling*, 257, 57-65.
- [3] Adonadaga, M. G. (2014). Climate Change Effects and Implications for Wastewater Treatment Options in Ghana. *Journal of Environment and Earth Science*, 4(8), 2225-0948.
- [4] Weber, J. M. (1992). Pathways for oxidative fuel provision to working muscles: ecological consequences of maximal supply limitations. *Experientia*, 48(6), 557-564.
- [5] Kosmas, C., Danalatos, N. G., López-Bermúdez, F., & Romero-Díaz, M. A. (2002). The effect of land use on soil erosion and land degradation under Mediterranean conditions. *Mediterranean desertification: a mosaic of processes and responses*, 57-70.
- [6] Seiler, R. A., Hayes, M., & Bressan, L. (2002). Using the standardized precipitation index for flood risk monitoring. *International journal of climatology*, 22(11), 1365-1376.
- [7] Stedinger, J. R., & Lu, L. H. (1995). Appraisal of regional and index flood quantile estimators. *Stochastic Hydrology and Hydraulics*, 9(1), 49-75.
- [8] Wikipedia contributors. (2019, January 13). Weighted arithmetic mean. In Wikipedia, The Free Encyclopedia. Retrieved 05:48, January 28, 2019, from [https://en.wikipedia.org/w/index.php?title=Weighted\\_arithmetic\\_mean&oldid=878218791](https://en.wikipedia.org/w/index.php?title=Weighted_arithmetic_mean&oldid=878218791)
- [9] Wikipedia contributors. (2019, January 23). Principal component analysis. In Wikipedia, The Free Encyclopedia. Retrieved 05:51, January 28, 2019, from [https://en.wikipedia.org/w/index.php?title=Principal\\_component\\_analysis&oldid=879791656](https://en.wikipedia.org/w/index.php?title=Principal_component_analysis&oldid=879791656)
- [10] Postel, S., & Carpenter, S. (1997). Freshwater ecosystem services. *Nature's services: Societal dependence on natural ecosystems*, 195.
- [11] Wikipedia contributors. (2019, January 24). Genetic algorithm. In Wikipedia, The Free Encyclopedia. Retrieved 05:57, January 28, 2019, from [https://en.wikipedia.org/w/index.php?title=Genetic\\_algorithm&oldid=880038508](https://en.wikipedia.org/w/index.php?title=Genetic_algorithm&oldid=880038508)