Contribution of Remote Sensing and GIS to mapping groundwater vulnerability in arid zone: case from Amour Mountains- Algerian Saharan Atlas

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Abstract. Protecting groundwater resource from pollution in arid zone is coming an important act for sensing development in this region calling for geomatics tools to characterize the geological and hydrogeological environment. The present work gives a new way to combine remote sensing and geographic information systems to elaborate groundwater vulnerability map of the aquifer namely Deffa watershed (in Amour Montains). This region is a good example of arid zones how know an important growth of agriculture, but there is under gap of geological, hydrogeological and soil knowledge. Firstly, we analyzed the Landsat 8-OLI image data with bands combination, ratios composition in RGB and filters to map the lithology's contours and lineaments. The false color composition of bands (765, 753, and 543) in RGB given the primary lithological delimitation. Supported by band rationing technique, we produced of 1/50000 geological map. The filter treatments given the lineament map superposed to the first one to realize geo-structural map. In addition, these images were used to elaborate pedology map, using Decision Tree (Slope, Redness Index and Lithology parameters). The resulting maps (lithology, lineament

and soil) and additional spatial information (aquifer type and deep of groundwater surface and precipitations…) were combined by GIS to map the groundwater vulnerability indexes by GOD and PI methods. Both of maps displayed four classes of vulnerability: between Low and Extreme in the first map, and Very low to High vulnerability in the second one. In the some areas, we have controversial values of vulnerability; this leads us to validate these maps using pollutions indicators (NO_3^-, NH_4^+ and SO_4^{2-}). The validation tools applied allowed to discriminate that the PI results are consistent with the spatial and temporal patterns of pollutants.

Keywords: Groundwater, Vulnerability, Remote sensing, GIS, Arid zone.

1 Introduction

The protection of groundwater resource from pollution in arid zone is a challenge, especially when the geological and hydrogeological conditions favorite immigration of pollutants. In arid and semi-arid countries with faster urbanization, and development of agricultural areas and intensification, the assessment of vulnerability of groundwater aims to be a tool for the decisionmakers and land planner since this allow to identify the most vulnerable zones and supports the sustainable water resources management (Secund et al., 1998; Saidi et al., 2011; Qian et al., 2012; Thomas and Duraisamy, 2018). The groundwater vulnerability mapping is one of the most applied tools to analyses the sensitivity of aquifers to pollution. However, to map efficiently the vulnerability to pollution requires a great deal of detailed information about surface and subsurface conditions. Furthermore, spatially explicit information is necessary, the scale of which must be sufficiently detailed to obtain reliable and accurate cartography.

Remote sensing (RS) is an ideal approach for detailed mapping of terrain features and surface structure and, thank to the several platforms, such as Copernicus Land Monitoring Service or XXX for accessing to free satellite imagery, this is an efficient tool for land monitoring (Zumsprekel and Prinz, 2000, Gomes et al., 2005, Zoheir and Emam, 2012, Van der Meer et al., 2012, Pournamdary et al., 2014a, Pournamdary et al., 2014b, Gabr et al., 2015, Eldosouky et al., 2017, Beiranvand et al. 2018, Bentaher and

Raji, 2020). Multispectral data is able to provide information on lithology or rock composition based on spectral reflectance (Ridwan et al, 2018).

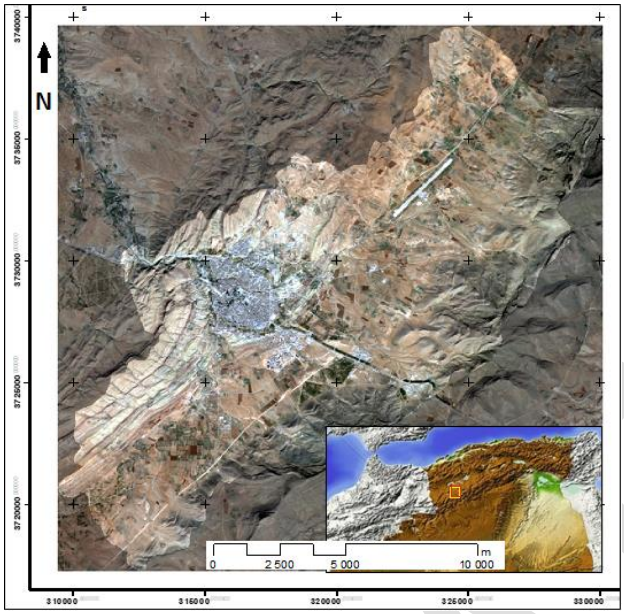
There are relevant gaps of knowledge and datasets for the study area of this work, Amour Mountains, central portion of Algerian Saharan Atlas. One of the most basic lack of information is a digital lithologic information at proper scale that allows going in depth in the hydrogeological study and the further groundwater protection. Under this framework, this work aims to produce a lithological map at 1/50000, covering the extend of the study area, by the treatment and interpretation of satellite images of Landsat OLI-8, to rectify the lithological contours and elaborate the lineament and soil maps is the first step of this work. These maps will contribute to the overall knowledge and the digital database available about Amour Mountains to enrich the scientific community.

Additionally, second part of this paper presents the groundwater vulnerability map to pollution calculated by GOD (Foster et al, 2007) and PI (Goldscheider et al, 2000) methods as example of use the digital maps produced under this work and as first approaches to protect the groundwater resource of this aquifer in arid zone. Vulnerability maps from both methods are discussed and validated, to check which approach present better protection of groundwater resources in arid zone.

2 Materials and Methods

The study zone is the Deffa catchment, that covers an area of 208.85 km^2, is part of Amour Mountains. Study catchment is a longue depression-oriented SW-NE surrounded by many mountains peaks (Fig. 1). In terms of geology, the formations comprise the Tertiary and Quaternary continental deposits, the outcrops range from the lower Callovian to the Berremian-Aptian-Albian. From morphology point of view, the main features are anticlines formed by sandstone-clay and carbonate series, from the Jurassic and the Cretaceous. The Cretaceous outcrops correspond to the less accentuated reliefs (Cornet, 1952). Hydrogeologically, the Infra-Cretaceous, Berremian-Aptian-Albian sandstones, Tertiary and Quaternary sediments form the major aquifer systems of the study site. The absence of impermeable layers causes hydraulic continuity conditions of all aquifers series. This multilayer aquifer is exploited by 400 wells and drillings (B.E.T.G.H, 2003). This valuable information served to estimate the groundwater level map based on the interpolation

of the well static water levels using the GIS tool inverse distance weighted method (Fig. 2).



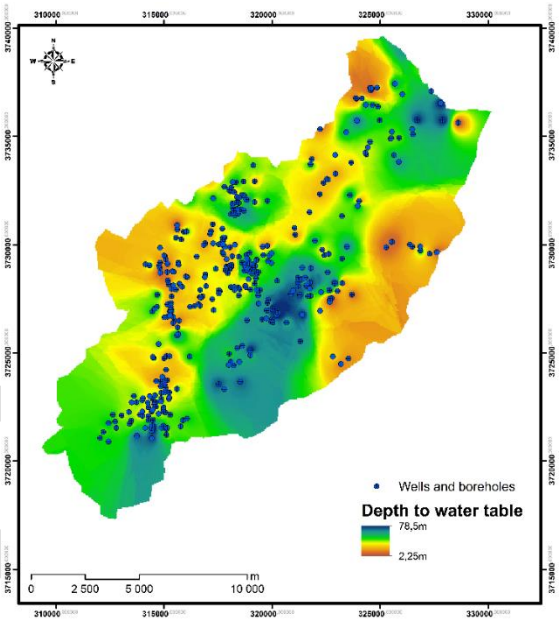


Fig. 1. Geographic situation of study region **Fig 2. Depth to water table in Deffa catchment**

Landsat 8-OLI images were acquired on third of December 2018. It has a nominal center path of 196 and row of 37 according to the Worldwide Reference System. From eleven bands available in the USGS Earth Explorer website (USGS, 2019), just seven first one (30 m of resolution) was used to the deferent pretreatment (radiometric calibration and atmospheric correction) and treatment (combination of bands, ration and filter). Different techniques were applied in band Image stacking: RGB composites, bands ratios, Vegetation and Soil indexes and Decision Tree for geo-structural, land occupation and soil maps. These were supportive to image interpretation and vulnerability mapping in GIS (Fig. 3). Differentiation and delimitation of rock types is done by creating color composite images; Standard bands combination such as 765 in RGB was prepared also band-rationing technique is used to detect outcrops limits in bare ground. The aridity of study zone made the rectification of geological limits easy due to the absence of vegetation cover. Additionally, different filters (0, 45°, 90° and 135°) helped us to elaborate lineament map. Both maps derived from images at 30m spatial resolution, being the derived maps at scale 1/50 000.

The NDVI (Normalized Difference Vegetation Index) (Jensen, 1996) give an idea of vegetation cover in study area.

On the other hand, there was an important lack of information regarding the pedological map. The strength of the relationships between soils properties and environmental variables (slope, RI (Madeira, 1993) and geological nature) were used to implement the Decision Tree (DT) (Fig. 4) for discriminate different soil types and outline a soil map. This prediction classification is frequently used to digital soil mapper (Hash, 2008; Moonjun et al, 2008; Engle et al, 2010). The DT algorithm was formulated based on the Raster calculating tools (if, then, else): slope, RI and lithology considered like nodes, controlled by conditions used by some authors.

After that, these maps were transferred to GIS. The details given by RS treatment (maps of lithology and lineament in 1/50 000) were combined with the information of geo-structural map (1/200000) in order to create the fracturing and lithological maps.

The digital terrain model was downloaded from (USGS, 2019) served to delimit the watershed of Deffa and establish topography map using GIS. Then, in GIS we created a database including all maps and data from bibliography (groundwater confinement factor, depth to groundwater, nature of vadose zone, precipitation). This constitutes the database to estimate the groundwater vulnerability maps by the application of GOD and PI methods.

The GOD method, because of its simplicity of concept and application, it is the first method used in this work. The GOD vulnerability index (Foster, 1987; Foster and Hirata, 1988) characterizes aquifer pollution vulnerability based on the following (generally available or readily determined) parameters (Foster et al, 2007):

- Groundwater hydraulic confinement, in the aquifer under consideration.
- Overlying strata (vadose zone or confining beds), in terms of lithological character and degree of consolidation that determine their contaminant attenuation capacity
- Depth to groundwater table or to groundwater strike in confined aquifers.

For more precision, the PI method is used to estimate vulnerability index taking account more parameters (infiltration, soil…). It is based on two factors; protective cover (P factor) and the infiltration conditions (I factor) (Goldscheider, 2003). The protective cover results from the thickness and hydraulic conductivity of all the strata between the ground

surface and the groundwater table (including soil, subsoil and unsaturated zone). The I factor indicates the degree to which the protective cover is bypassed as a result of surface and near-surface concentration of flow. The protection factor π is obtained by multiplication of P and I. More details about PI can be found in (Goldscheider et al, 2000).

Validation of groundwater vulnerability maps can be performed by several ways (Marín et al. 2015). Among the methods the comparison of the vulnerability index/map with water quality parameters are the most used with confident results (Ghazav and Ebrahim, 2015). To validate vulnerability maps, we used the pollution indicators concentrations in groundwater from water analyses: NO_3^- of 56 boreholes and SO_4^{2-} and NH_4^+ of just 17 one (ADE, Algerienne Des Eaux 2018-2019). The concentrations of these elements in the groundwater collected of these boreholes are compared with both of GOD and PI maps. Nevertheless, just nitrate concentration was chosen for correlation study.

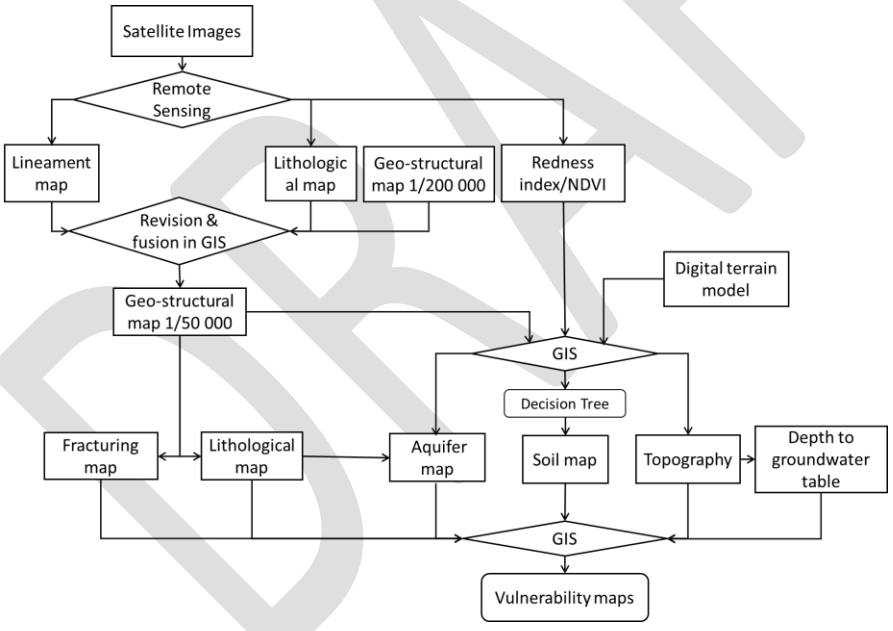


Fig. 3. Deferent steps of data treatments.

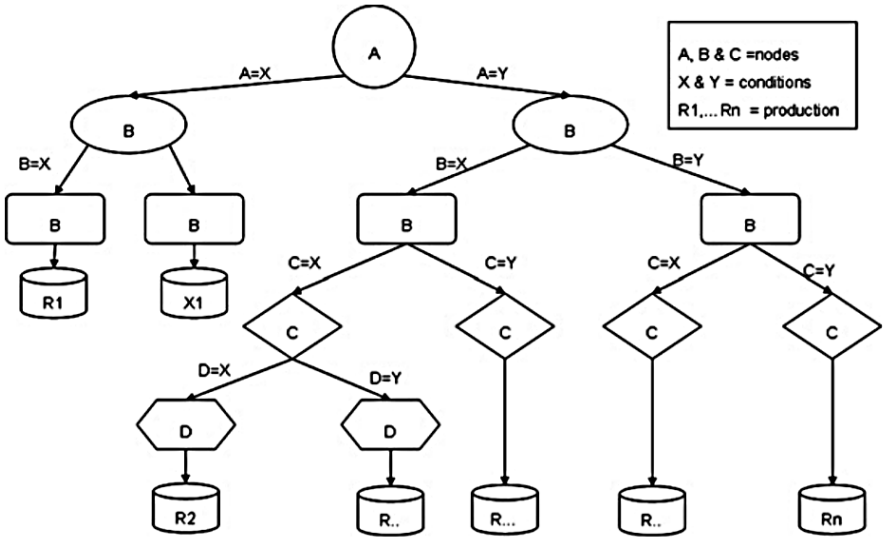


Fig. 4. The exemplifier of a simple decision tree structure (Moonjun et al, 2010)

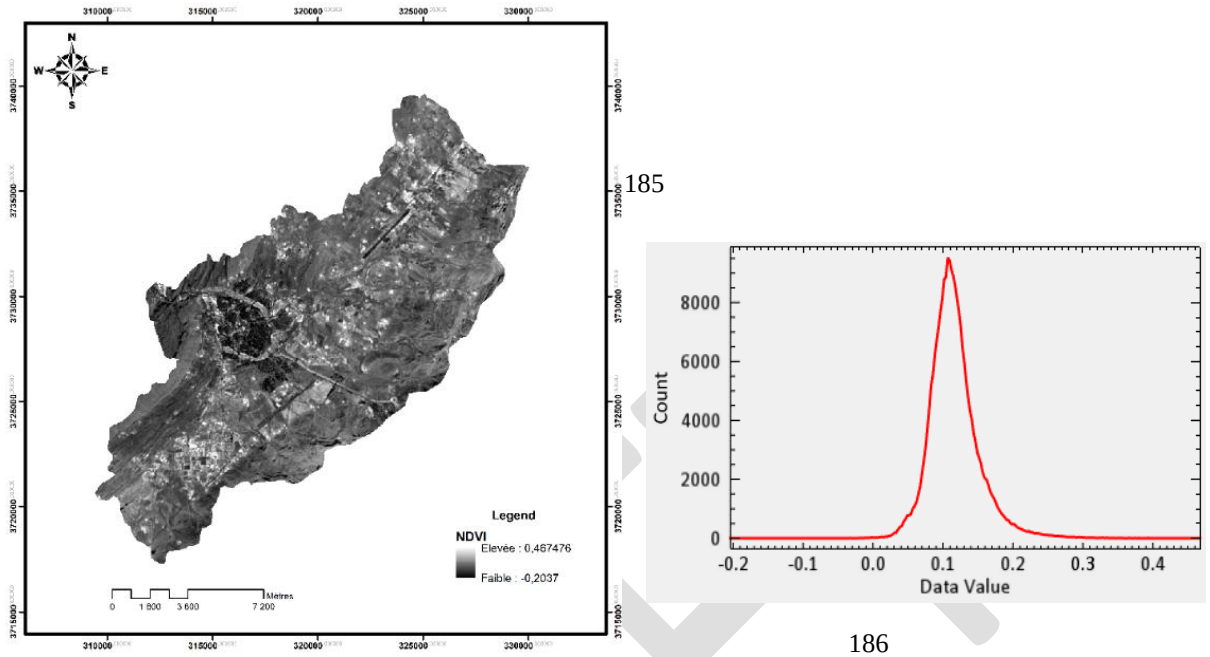
3 Results

3.1 Remote sensing treatment

In this study, we used RS treatment to identify the lithology, lineament network and soil nature, in Deffa watershed. Prior to attempting the different classifications, the pre-treatment (radiometric correction and atmospheric correction) was performed to achieve reflectance data. NDVI is considered in many studies (Martiny et al, 2006; Guerrero et al, 2016, Kazi Tani, 2016; Yadav and Borana, 2019) like a significant parameter to mapping land occupation in arid zone; in figure 5a, NDVI presented a low value, between -0.2 and 0.45. In the histogram of NDVI (Fig. 5b), the values have a “Bell Curve” at 0.1, more than 32% of study surface is in this first class (<0.1). Between 0.1 and 0.3, we have 67.7%: degraded or absence of vegetation cover. Just 0.1% present high value of NDVI (>0.3-0.45) indicate a considerable vegetation cover.

For the first category of analyses, the important results that we based to classify the lithology are color composite (765, 753 and 543) (Fig. 6) and ratios assembling in RGB: (6/7, 6/4, 6/5) (6/7, 4/2, 5/4) and (7/6, 5/6, 2/4) (Fig. 7). To elaborate the lineament map, we used four filter with directions: 0, 45°, 90° and 135°. The assembly of filter results is show in figure 8a. The lineaments rosacea is presented in figure 8b.

The validation of lithology and lineament network were doing in GIS. The figure 9 present the geo-structural map of Deffa watershed.



a. **b.**

Fig. 5: (a) NDVI image and (b) histogram of the study region.

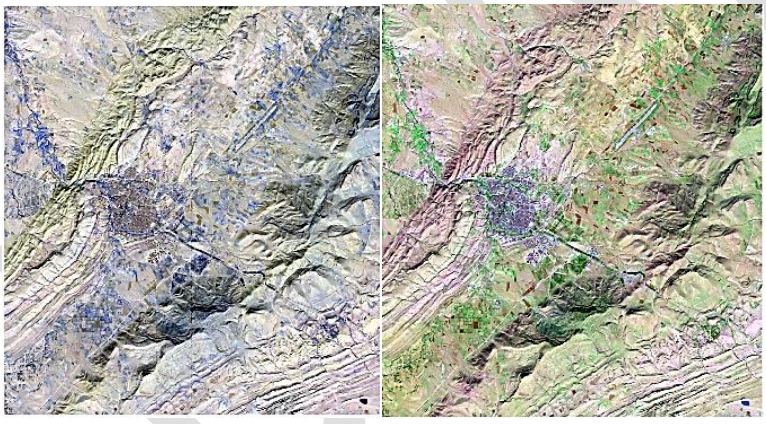
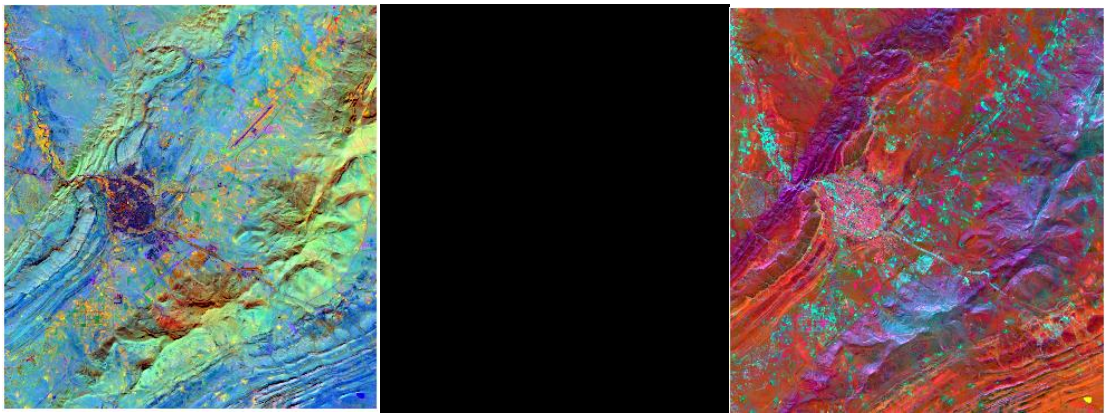


Fig. 6. Landsat 8-OLI color composite image, RGB=765, 753, 543.



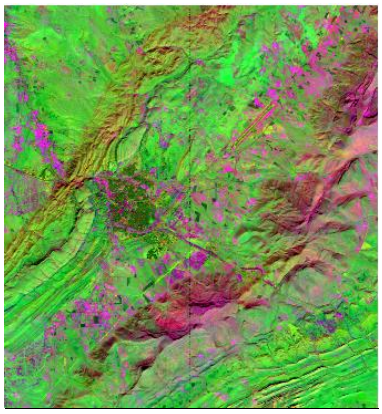
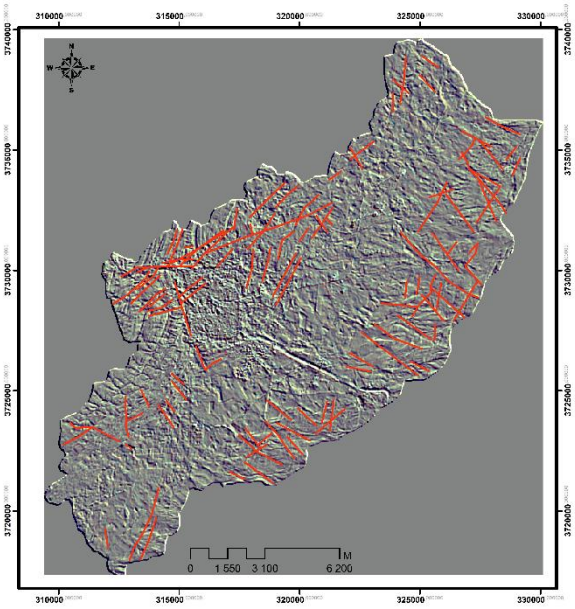


Fig. 7. Landsat 8-OLI bands ratios assembling in RGB: (6/7, 6/4, 6/5) (6/7, 4/2, 5/4) and (7/6, 5/6, 2/4).



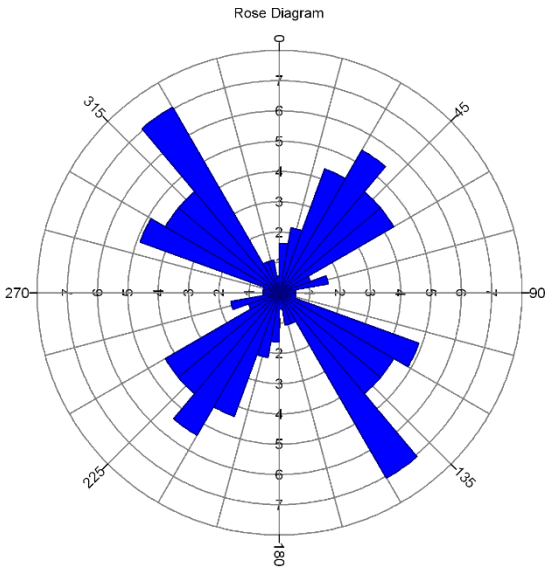


Fig. 8. (a) Landsat 8 OLI filter (135°) with network lineament, (b) rosacea of results lineament

The second category of RS treatment concerned pedology classification. For that, we calculated the RI (Fig. 10) and integrated it in DT with slope and lithology parameters (Fig. 11). The results were four classes of soil and land occupation (Fig. 12): Lithosols, Poorly Developed Soil (P. D. Soil), Calcisols and Fersialsols.

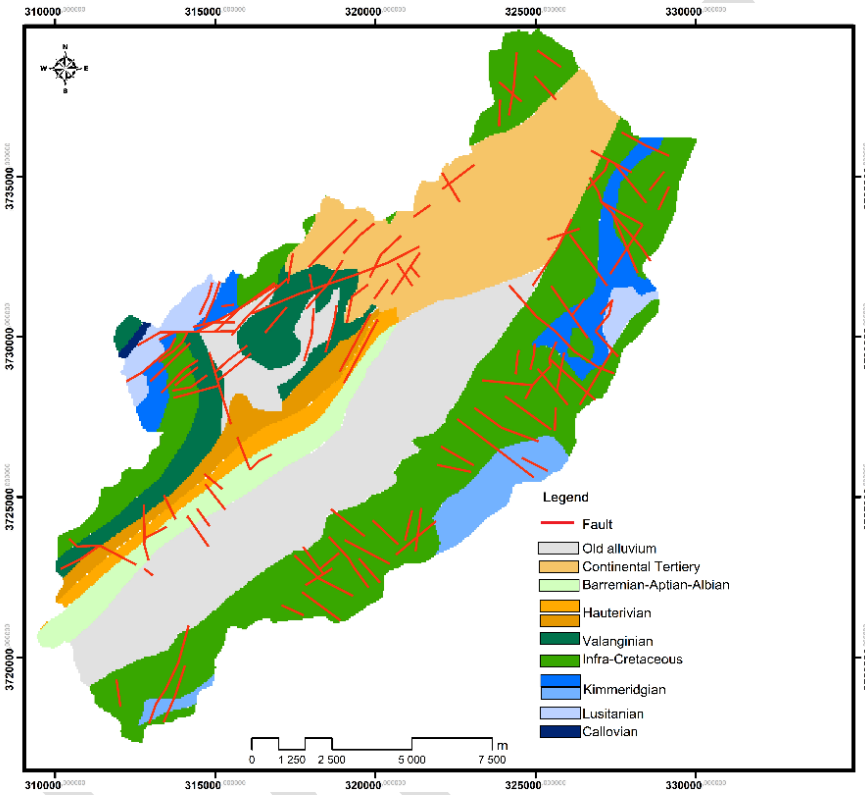


Fig. 9 Geo-structural map fusion all data in GIS.

3.2 GIS and vulnerability indexes

The second step involved the generation of a GIS database to compile all relevant datasets that are input data for assessing the vulnerability of groundwater to the pollution according to GOD and PI methods (Foster et al, 2007; Goldscheider et al, 2000). These include the spatial RS products and field datasets.

3.3 GOD map

Groundwater confinement, Overlying strata and Depth to groundwater table construed three layers used to mapping GOD index (Fig. 13). The geo-structural map result of RS, served to elaborate O layer, identifying lithological character and degree of consolidation of unsaturated zone or confining beds. This approach displayed four classes of vulnerability, between low and extreme, which occupied most of basin surface, mainly in boundaries of the basin.

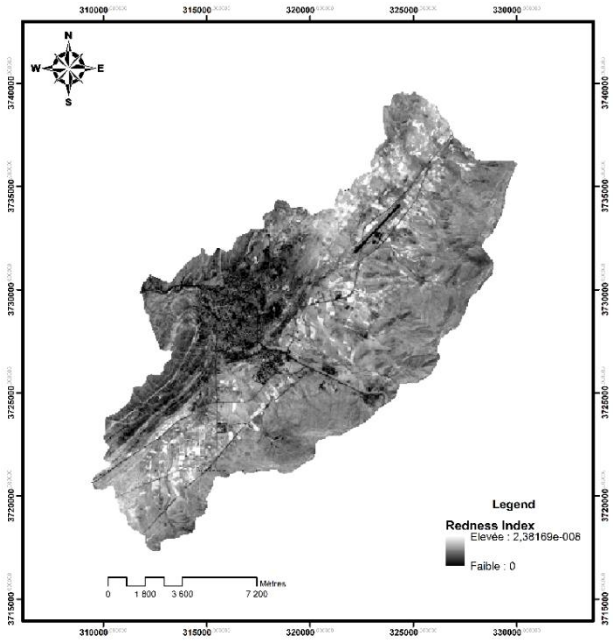


Fig. 10. Image of Redness index of the study area.

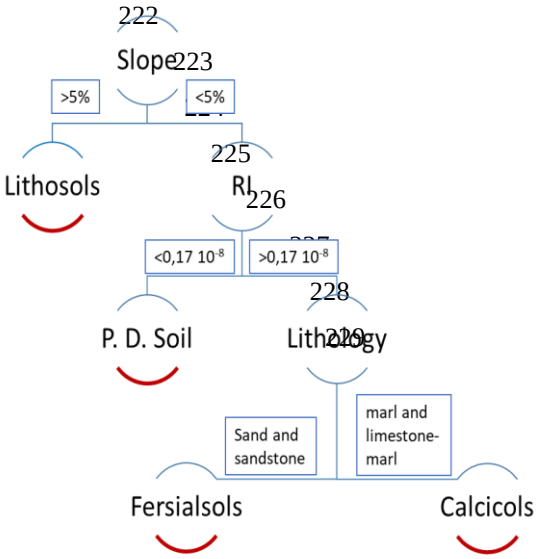


Fig. 11. Four classes resulting of DT treatment in

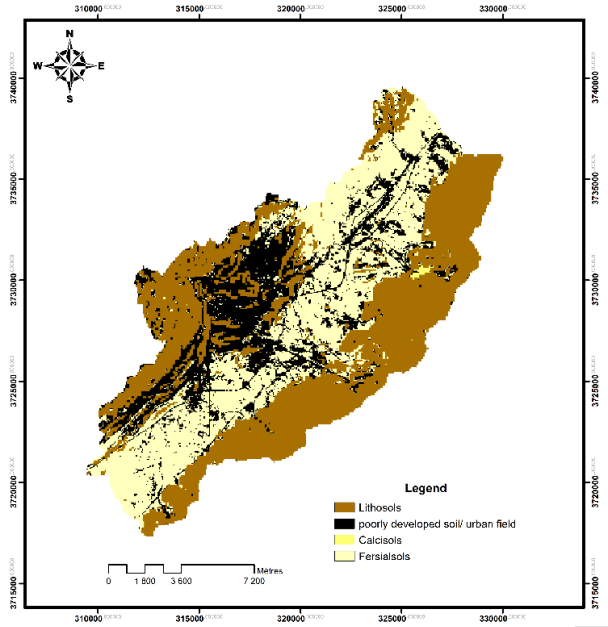


Fig. 12. DT map of study area

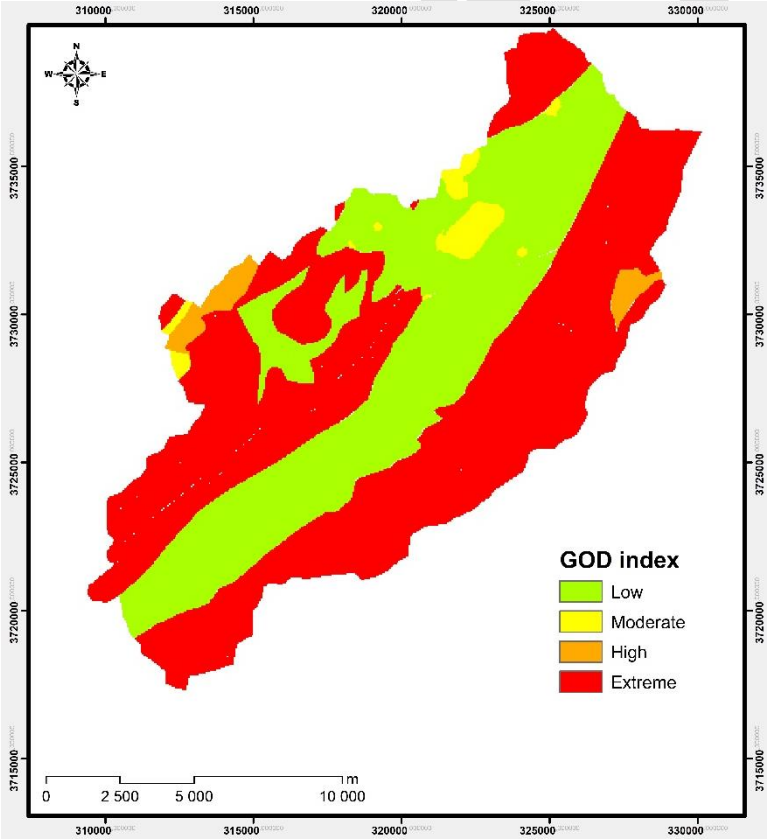


Fig. 13 Vulnerability map of GOD

3.4 PI map

Also, using and integrated different maps of RS processing: lithology, lineament and soil nature, in GIS database, allows to calculate Protection and Infiltration indexes. These layers served to mapping vulnerability using PI method. The final vulnerability map is depicted in figure 14. It shows four classes: very low to high vulnerability. It is noted that the moderate vulnerability occurs, principally in the middle of the watershed.

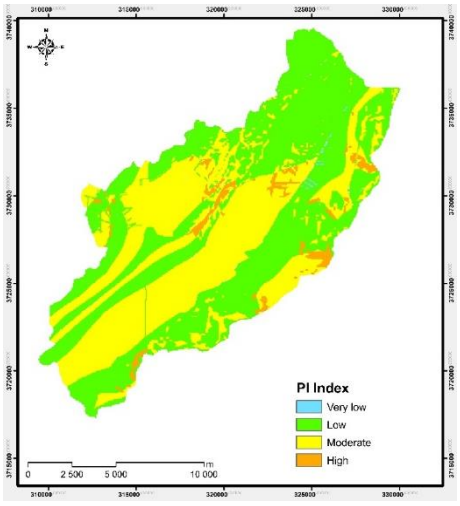


Fig. 14. Vulnerability map of PI

4 Discussion

The low values of NDVI indicate absence vegetation cover in study zone, which facilities the interpretation of satellite images.

The main features that are usually visible by RS treatments are the lithological distributions as well as the faults, shears and fractures. For that reason, band combination images for this study area were created to show the delimitation of outcrop limits for each image scene who was processed through creation of image stack (RGB and ratio):

Bands (7, 6 and 5) gave a false color image composite with an enhanced image with the rocky outcrops shown in shades of light purple and olive. The vegetation apparent on blue. Bands 7, 5 and 3 give the green shade to the clay-limestone formation and the purple to sandstone one. Last band (543) combination give the red nuance for agriculture area, and pink and gray for sandstone and claying outcrops. Accordingly, a band ratio color composite was prepared by assembling the ratios: (6/7, 6/4, 4/2), (6/7, 4/2, 5/4) and (7/6,

5/6, 2/4) in RGB, respectively. As it is clear from these images, the limit of formation is more obvious that in band combination maps.

The directional filters used to mapping lineaments of the Deffa watershed, which is perfectly overlap with geomorphological structures of study area. The lineament rosacea shows the directional frequency of the mapped lineaments over the area of study. The rose diagram of the detected lineaments show two prominent trends in the directions of the N40° and N150°, which are also the principal directions of the regional structures in Amour Mountains (Stamboul, 2005).

For pedology treatment, we used RI to identify the soil nature. The important values coincided to the agricultural area. The low values indicate complete absence of soil or, in our case urbanisation area. Set of parameters involve developing soil in arid zone, the authors used frequently the topography, lithology and soil indexes (Color index, Brightness index…) to predicted soil map (Kazi Tani, 2016; Ben-Dor et al, 2006, Zeraatpisheh et al, 2018; Gray et al, 2016; Escadafal and Pouget, 1987). In our case, the DT was elaborated using the environmental covariates: slope, RI and lithology. The map resulted four classes of different soil nature: Lithosols covered 42.67% of the area corresponding a slope high than 5%. In the slightly sloping region, depending on the RI (lower values), 21% is occupied by poorly developed soil and urban filed. The rest of surface, the lithology nature conditions shows existence of 35% Fersialsols and just 0.19% of Calcisols.

All the aforementioned information were compiled in a GIS database to map vulnerability of groundwater in watershed of Deffa using GOD and PI methods. The resulting maps clearly showed differences. More than 57% and 37 % of watershed surface present Extreme and Low vulnerability in GOD map but the 53% of area has low index of PI and 43% for moderate vulnerability. Additionally, to analyse the spatial pattern of the vulnerability classes, it is possible to identify that there are controversial areas:

- Limits of watershed: while these areas are extremely vulnerable in GOD, they are in the low, moderate and high classes in PI: In these areas, the lithology nature and depth of water table increase GOD index, but many details taken by PI method highlight and specified the many areas with different vulnerability.

- Center of watershed present low GOD index but moderate value of PI index: this is because GOD uses depth to water table in vulnerability assessment, whereas PI neglects this parameter. In depression the high depth to water table, make them low vulnerable in GOD map. Contrary to PI map, the flat topography, favorite infiltration of pollutant, so these zones are more vulnerable.

The natural nitrate concentration in groundwater under aerobic conditions is a few milligrams per liter (WHO, 2011), the study area presents concentrations between 3 and 55 mg/L. While 50 mg/L is considered very high concentration for drinking water.

The comparison of chemical concentration in groundwater samples of boreholes and both of maps show that the average of NH_4^+ and SO_4^{2-} concentration in low class is higher than extreme one for GOD map.

The Spatial distribution map of nitrate (fig. 15) showed that high concentrations of NO_3^- is in the center of the basin coinciding with moderate and high PI index. Correlation coefficient is one of the parameter useful in vulnerability map validation (Lake et al. 2003, Kumar and Krishna, 2018; Mfumu Kihumba et al, 2017). The relationships between the vulnerability indexes and NO_3^- concentration (fig. 16) show that PI index correlates negatively with nitrate concentration. This means that high PI values, that represent a high degree of natural protection and low vulnerability, correspond with lower values of nitrates, being consistent with the expectation. However, GOD index showed ???

Furthermore, the Spearman's rank correlation coefficient (Bonham-Carter, 1994) was calculate for PI and GOD indexes; the values of -0.86 and 0.47 have been obtained respectively, indicating that vulnerability map by PI approach matches to some extent aquifer pollution state as expressed by the nitrate distribution in the groundwater.

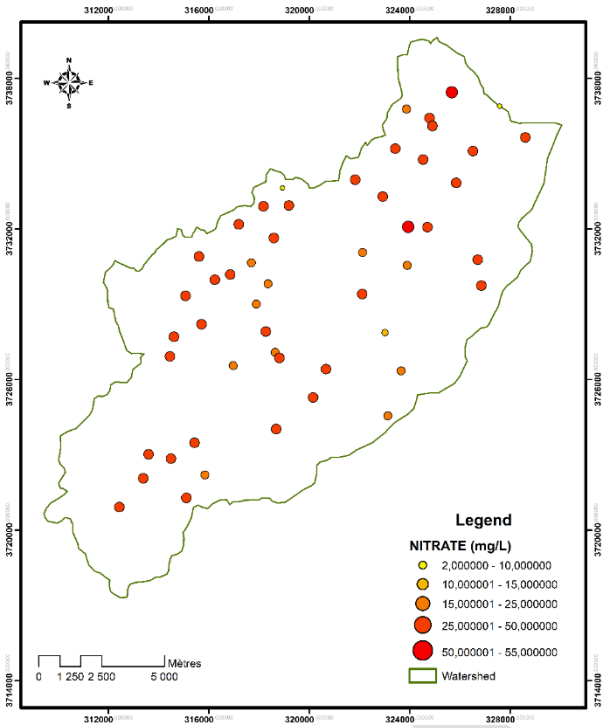


Fig. 15. Spatial repartition of NO_3^-, used to validate of vulnerability maps

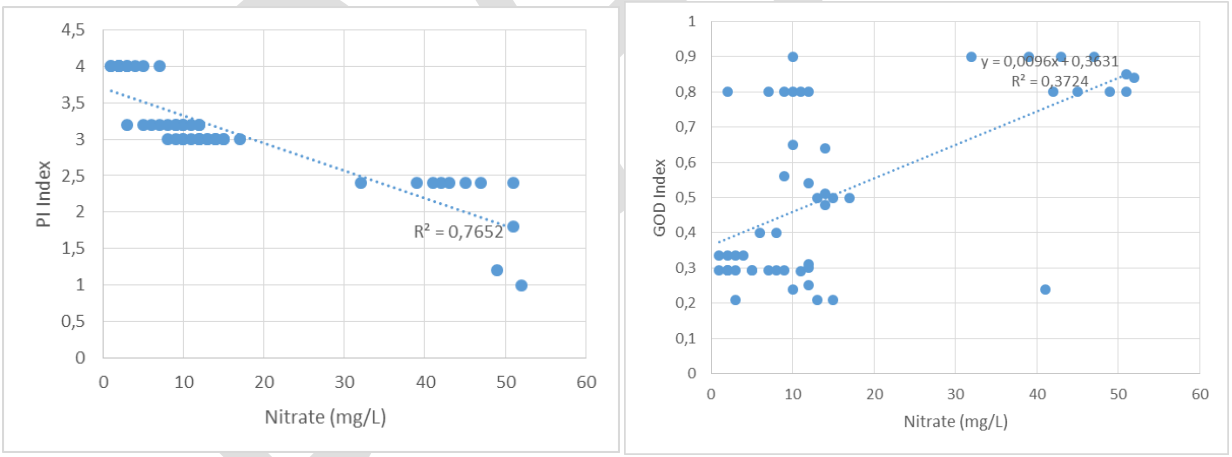


Fig. 16. Correlation for PI and GOD Indexes by scatter plot.

5 Conclusions

In this research, a combination of analysis techniques of spatial information were used to sensing vulnerability of Deffa catchment to pollution. The treatment of Landsat 8-OLI multi-spectral bands is presented. Based on the interpretation of RGB combinations of bands and ratios, and deferent filter, the geo-structural map was produced in big scale.

The other indexes were calculated (NDVI and RI) and involved in DT to mapping soil nature. That help us to calculate GOD and PI index. The result of these map indicated high to extreme vulnerability in big part of study region, however the comparison with concentrations of pollutants in groundwater revealed that the PI approach suits Deffa catchment more than GOD because GOD neglects important factors that affect vulnerability in arid zone. These factors include topography, precipitation regime, fracturing, in addition to soil nature.

The resulting vulnerability map can be used to delineate areas for groundwater protection and management of land occupation

Many analysis technics can be applied to multispectral imagery to extract specific spatial information. For this, it is important to make the best use of the merged techniques in the development of groundwater resources.

Data Availability:

The satellite images that support the findings of this study are available online: https://landsat.usgs.gov/landsat-missions-timeline.

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