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Optimal site selection for an optical-astronomical observatory in Pakistan using Multicriteria Decision Analysis

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Abstract An astronomical observatory is the core component of any astronomical research facility that connects astronomers with their lab: the Cosmos. The research quality of an astronomical facility is rooted in the precision of data, collected by its observatory. For optimal performance, an observatory is sited while considering certain astronomical, environmental, geological and social parameters. This study aims to identify the potential sites in Pakistan for locating an optical-astronomical observatory using the Multicriteria Decision Analysis (MCDA) technique. The study uses the Analytic Hierarchy Process (AHP) for deriving the influence weights of nine evaluation criteria: Photometric Night Fraction; Night-time Sky Brightness; Sky Transparency; Aerosol Concentration; Altitude; Terrain Slope; Accessibility; Seismic Vulnerability; and Landuse/Land Cover. On the basis of experts' opinions and previous studies, the evaluation criteria have been ordered in two possible preference sequences for identifying their influence weights with respect to each other for taking part in MCDA. Consequently, the process of MCDA identified certain areas with respect to each preference sequence, whereas some areas were found to be suitable according to both preference sequences. The study synchronizes the required eclectic data into an evaluation matrix that augments the process of astronomical site selection. In the future, this study will be useful for astronomical societies and for furthering astronomical research in the country.

Key words: astronomical instrumentation — methods and techniques: data analysis — astronomical instrumentation — methods and techniques: site testing — general: miscellaneous

1 INTRODUCTION

Any site with low artificial lights, cloud-free night sky; good astronomical seeing; and having an environment with minimal water vapor, haze, fog and particle scattering can ideally be considered for optical-astronomical study (Hudson & Simstad 2010; Hotan et al. 2013). However, the selection of a potential site requires several other factors encompassing: climatology, geography, geology and social aspects.

This paper aims to derive optimal locations in Pakistan for siting an optical-astronomical observatory by analyzing multiple aspects/criteria of astronomical site selection. For this purpose, the study used Geographical Information System (GIS) as a platform in combination with Multicriteria Decision Analysis (MCDA). GIS is a method of storing, analyzing, modeling and manipulating spatial data. On the other hand, MCDA is a powerful analysis tool that formulates and analyzes multiple criteria into an equation through Weighted Overlay and Index Rank Mapping. The combination of GIS and MCDA enables the decision maker to analyze multicriteria decision problems through spatial analysis techniques. GIS based MCDA is a dynamic method that facilitates the analysis of geographic information in a flexible manner, unlike traditional GIS that performs analysis over static parameters (Malczewski 2006). By its nature, this decision problem is specific to a certain type of MCDA that is the Multi Attribute Decision Making (MADM) technique in which various quantitative and qualitative criteria are considered using a probabilistic relationship based on certainty levels of evaluation criteria.

The field of astronomy has very little integration with satellite based spatial data that are capable of synoptic viewing. There are many environmental/meteorological factors in astronomical site selection – such as cloud cover situation, concentration of aerosols, night-time sky brightness, etc. – that can efficiently be addressed through satellite based data. In this way, the satellite data allow analysis of the situation of any parameter for several years that can augment and narrow down the probable area for on-site measurement instead of replacing it completely.

2 PREVAILING CRITERIA AND THEIR DATASETS

2.1 Evaluation Criteria

The evaluation criteria for a particular decision problem should be identified on the basis of relevant literature review and previous analytical studies (Pitz & McKillip 1984). Each evaluation criterion depicts a certain dimension that defines the depth and nature of that multicriteria decision problem (Malczewski 1999). The selection of evaluation criteria for MCDA is based on the desirable analysis dimensions with respect to their importance, as required by the decision maker. Therefore, some of the evaluation criteria are ignored due to not having significant influence over a certain decision problem (Keeney & Raiffa 1976). On the basis of experts' opinions – from the National Space Agency of Pakistan – and by referring to previous research, we have identified nine evaluation criteria for taking part in the process of MCDA (see Table 1).

3 DATASETS FOR THE EVALUATION CRITERIA

The study analyzes nine evaluation criteria, for which various types of datasets have been considered that are spatial in nature. As discussed, the satellite imagery and its derived products can provide synoptic coverage that will enable analysis of the situation of any criterion throughout the country. These evaluation criteria do not have any defined threshold ranges for such studies. The evaluation criteria for any site selection can be identified with reference to their direct/inverse relation to the decision problem. In other words, if the value of a criterion is directly related to the appropriateness of a site, it is considered as a directly related factor and vice-versa. In this scenario, Criterion Maps are generated for each criterion that registers the suitability of a site with respect to certain ranges of values within the dataset of that criterion. For example, in the criterion maps of the datasets, the lower values of Cloud Cover, Aerosol Concentration and Terrain Slope would be more favorable in contrast with the higher values, whereas it would be the reverse for the Altitude. In order to homogenize the datasets, the continuous ranges of the datasets are classified into equal numbers of categories for taking part in MCDA. Details of evaluation criteria and the datasets used for this study are listed below:

Photometric Night Fraction

Photometric night-time is the specific time during a night when there are no clouds more than 5 degrees above the horizon during the specific hours when the Sun is at least 18 degrees below the horizon and a night with at least six consecutive hours of photometric night-time is referred as a photometric night (Sarazin 1995). Also, the ratio between photometric nights and the total number (365) is known as photometric night fraction. In this way, the factor is completely dependent on cloud cover of that area.

The Level-2 Cloud Product of the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor uses infrared and visible reflected solar radiance for identifying the cloud top temperature, cloud top height, effective emissivity, cloud phase (such as ice or water and in terms of light permissibility), and cloud fraction under both daytime and night-time conditions (Masuoka 2015).

This study used the MOD06-L2 (Night-Time Cloud Fraction) product with spatial resolution of 5 km for estimating the cloud occurrence. The data were acquired from 2015 January 1 to 2017 June 30 (1083 datasets). The mean of these datasets provides temporal and seasonal variation in cloud occurrence that give the average density of clouds in the country (see Fig. 1).

Night-time Sky Brightness

Night-sky brightness is a phenomenon in which the incoming light is dimmed because of various sources of light pollution. These unwanted lights are commonly from anthropogenic sources, aurorae and sodium layer nightglow in the mesosphere. National Oceanic and Atmospheric Administration (NOAA) provides night-time light data through Suomi National Polar Partnership - Visible Infrared Imaging Radiometer Suit (SNPP-VIIRS). These data can be used for several socioeconomic purposes: such as identifying the population density and spotting power outages in known urban areas. Apart from anthropogenic lights, it can detect lightning, fishing fleet navigation lights, gas flares, lava flows and auroras (Blumenfeld 2019). For night-time light data, VIIRS provides a $0.55\,\mathrm{km}^2$ footprint at nadir ($742\,\mathrm{m}\times742\,\mathrm{m}$ pixel) in contrast with Operational Line-Scan System (OLS) of Defense Meteorological Program (DMSP) that has a footprint of $25\,\mathrm{km}^2$ ($5\,\mathrm{km}\times5\,\mathrm{km}$ pixel) at nadir (Elvidge et al. 2013). This study considered SNPP-VIIRS night-time data for estimating night-sky brightness that is available in the form of monthly and annual composites. Hypothetically, the lights of a certain area always increase with time because of urban sprawl expansion, therefore, we use the latest imagery of an area (see Fig. 2).

Sky Transparency

Sky transparency refers to the level of clear sky (free from atmospheric turbulence) that allows the observations of

Table 1 Evaluation Criteria for MCDA

No	Criteria	Parameter	Role in MCDA
1	Photometric Night Fraction	Cloud Cover	Higher number of cloud free nights increase the suitability of a site Pollution
2	Night-Sky Brightness	Anthropogenic Light	Higher concentration of artificial lights decreases the suitability of a site
3	Sky Transparency	Aerosol Concentration	Higher concentration of aerosols in the atmosphere decreases the suitability of a site
4	Altitude	Elevation from Sea Level	High altitudes suitable for an astronomical site (while considering the workable temperature and air pressure)
5	Terrain Slope	Slope/Gradient	Areas with lesser gradient values are suitable for site construction
6	Seismic Vulnerability	Fault Zones	Areas furthest from any fault line are suitable for site
7	Wind Speed	Wind Speed	Areas under high wind speed are not suitable for site construction
8	Accessibility	Road Access	Areas close to roads are suitable for the site
9	Landuse/Land Cover	Landuse/Land Cover	Certain landuse/land cover is more feasible for site

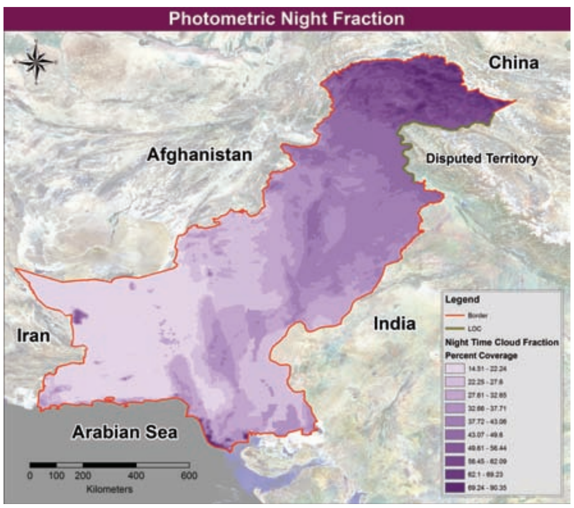

Fig. 1 Photometric night fraction (cloud cover).

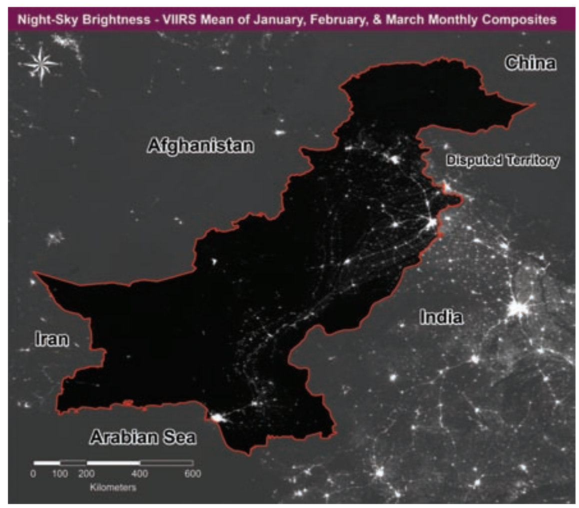

Fig. 2 Night sky brightness (anthropogenic light pollution).

faint celestial bodies by enabling optimal performance of a telescope. It is mainly affected by aerosols that comprise small dust particles, liquid droplets, smoke, pollen and water vapors (Hotan et al. 2013). The Aerosol Product of the MODIS sensor monitors the aerosol optical thickness, its types over oceans and some parts of continents (NASA-MODIS Atmosphere 2009[1]). The product provides 10×10 km swaths and is available through Terra and Aqua Platforms namely; MOD04-L2 and MYD-04-L2 respectively (NASA-MODIS Atmosphere 2009[2]).

This study used the MOD04-L2 (Corrected Optical Depth Land) product for monitoring the aerosol situation that varies with time and space. For estimating temporal and climatic aerosol variation, the imagery from 2015 January 1 to 2017 August 31 (961 datasets) was acquired. The mean of these datasets provides the optical thickness of the aerosol ranging from 0 to 3 for calculating the average density of aerosols (see Fig. 3).

Altitude

Altitude is one of the most important criteria that critically influence astronomical data. As a rule of thumb, altitude has been considered to be the primary aspect for any astronomical site selection study; however, any range over an altitude of 5000 m cannot be feasible because of poor accessibility, low oxygen level and harsh weather: these areas are not classified as a workable environment. The study used Shuttle Radar Topography Mission (SRTM) – 30 m data for a Digital Elevation Model (DEM) (see Fig. 4).

Terrain Slope/Gradient

Slope gradient is the key element to define the slope variation in an area and its suitability for construction. The

[1] `https://modis-images.gsfc.nasa.gov`
[2] `https://modis-images.gsfc.nasa.gov`

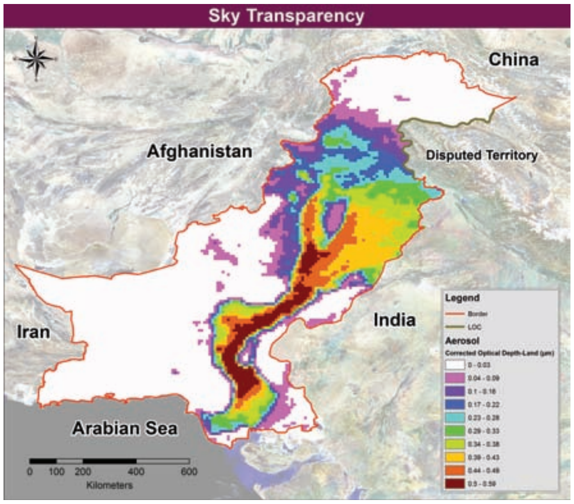

Fig. 3 Sky transparency (aerosol concentration).

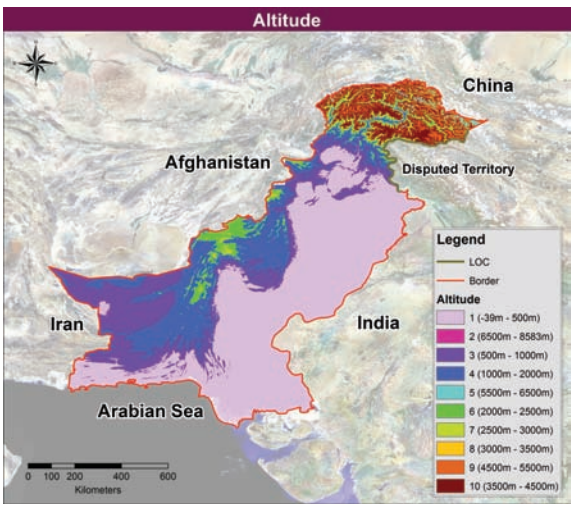

Fig. 4 Altitude (elevation from sea level).

terrain slope for construction / site selection is commonly computed in percent, in which a slope of 45° is considered to be 100% slope. The relation between these two units can be expressed through following equation

$$\mathrm{PercentSlope} = [\tan(\mathrm{Degrees})] \times 100\,.$$

In this study, the SRTM-DEM (30 m) is applied to calculate the slope (see Fig. 5).

Seismic Vulnerability

Geomorphology/geology of an area is one of the key parameters for any site selection that influences its efficiency, stability and construction cost. The study uses the data on seismic risk zones (Pakistan-Meteorological-Department 2007) and major faults (Geological Survey of Pakistan 1964) for calculating the seismic feasibility (see Fig. 6).

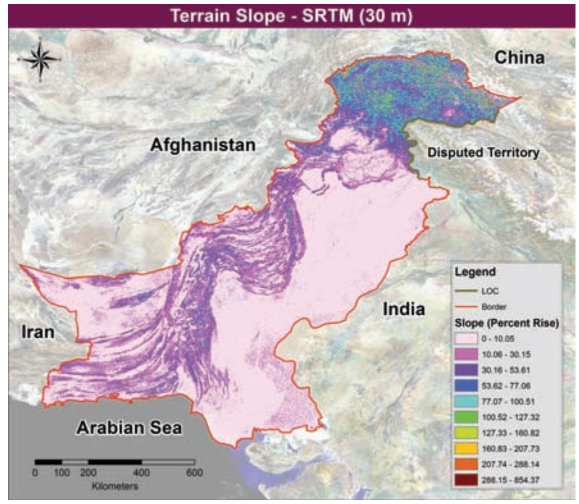

Fig. 5 Terrain slope/gradient.

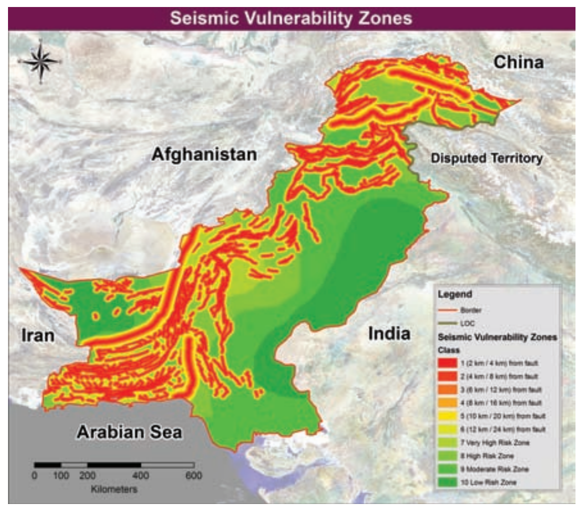

Fig. 6 Seismic vulnerability.

Wind Speed

Wind Speed affects astronomical seeing in the same way as aerosols. The typical mean value of astronomical seeing should remain around 0.6 that increases around 20–30 percent with the speed of wind (Beckers 2009). For dealing with this criterion, the study uses 'Wind Zones' identified by the Pakistan Meteorological Department (PMD) that divides the country into seven wind zones (see Fig. 7).

Accessibility

Any rational site selection needs to consider the factor of accessibility for ensuring efficient access to the site. This study considers the major road network as defined by the Survey of Pakistan (SoP) at a scale of 1:50 000. The minor roads, streets and tracks in northern areas of the country have been augmented using satellite imagery, as most of

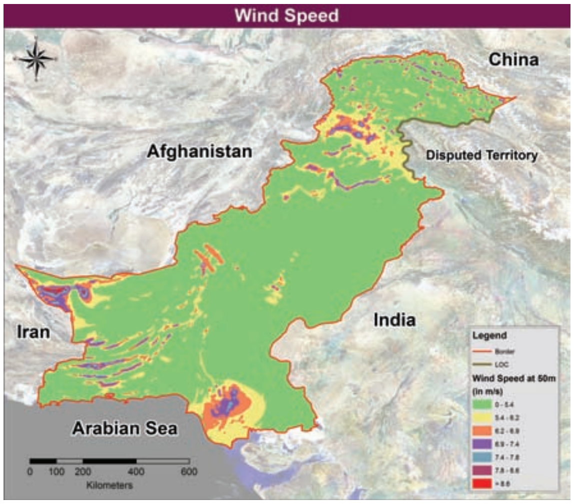

Fig. 7 Wind speed.

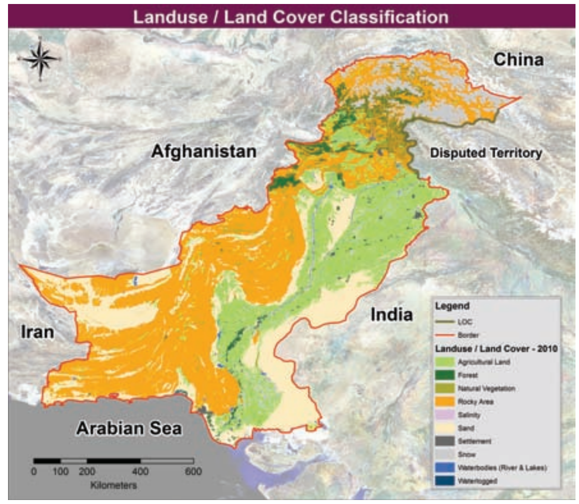

Fig. 9 Landuse/Land Cover classification.

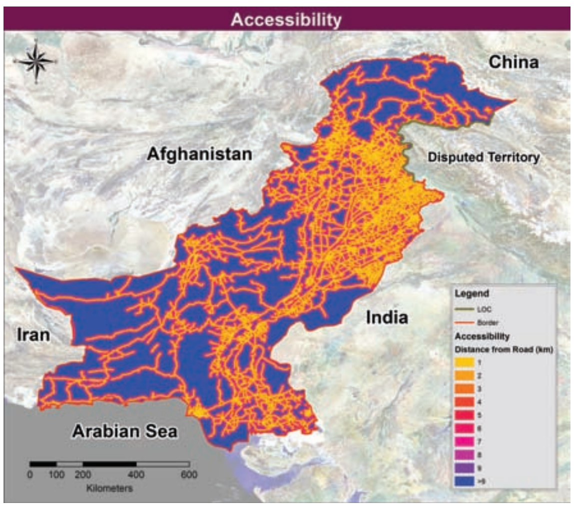

Fig. 8 Accessibility (road network).

the mountainous areas are connected via minor roads and tracks (see Fig. 8).

Landuse/Land cover

Landuse/Land Cover is another key aspect that directly influences the decision rule set specifically for site selection. A human settlement has an inverse relationship with a desirable astronomical site because of anthropogenic light pollution, which is one of the undesirable conditions for an optical-astronomical observatory. Moreover, for designing an optimal site selection algorithm, the analysis should include the Landuse details such as water bodies, forests, agriculture and barren lands before selecting a site for the observatory. The study uses Landuse/Land cover Classes of National Environmental Information Management System (NEIMS) developed by Pakistan's Ministry of Climate Change in collaboration with the Pakistan Space and Upper Atmosphere Research Commission (SUPARCO) (see Fig. 9).

Synoptically, the evaluation criteria and their pertinent datasets used for the study are listed in Table 2.

4 MULTICRITERIA DECISION ANALYSIS

MCDA analyzes the spatial data in flexible ways through Weighted Overlay and Index Rank Mapping, in contrast with the traditional GIS that deals with the static parameters using Boolean Overlay. Criteria weighting is the crux for any decision problem, solved using MCDA that defines their comparative influence over the decision with respect to the priorities of the decision maker. According to the opinion of experts from the National Space Agency of Pakistan and with reference to the previous astronomical site selection studies, the study considers two orders of preference sequences for the evaluation criteria. These preference sequences will determine the influence of evaluation criteria in the process of MCDA and will serve as two case studies for the research (see Table 3).

The study uses the Analytic Hierarchy Process (AHP) for identifying the influence weights of evaluation criteria. AHP is a pairwise comparison method which is a highly reliable technique for assigning criteria weights that compare two criteria at a time to avoid unnecessary complication for the decision maker. However, the pairwise comparison method has been criticized for comparing criteria relatively without considering the scale of their measurement (Malczewski 1999). The consistency of criteria weights has been validated using consistency ratio (CR=0.0987). Table 4 shows the influence weights of evaluation criteria with respect to both preference sequences for taking part in MCDA.

For the process of MCDA, we need the criterion map of each dataset in which the datasets are required to have

Table 2 Evaluation Criteria and their Pertinent Datasets

No	Criteria	Parameter
1	Photometric Night Fraction	MOD06_L2 Nighttime Cloud Fraction
2	Night-Sky Brightness	SNPP-VIIRS Nighttime Light Data
3	Sky Transparency	MOD04_L2 Corrected Optical Depth Land
4	Altitude	SRTM-DEM (30 m)
5	Terrain Slope	Calculated using SRTM-DEM (30 m)
6	Seismic Vulnerability	Seismic Zone Maps by PMD and Fault Line Map by Geological SoP
7	Wind Speed	Wind Speed Map (at 50 m altitude) by PMD
8	Accessibility	SoP Map at the Scale 1:50 000
9	Landuse/Land Cover	NEIMS and SUPARCO

Table 3 Preference Sequences of Evaluation Criteria

Evaluation Criteria	Preference Sequence 1	Preference Sequence 2	PriorityOrder
Criteria 1	Photometric Night Fraction	Altitude	1
Criteria 2	Night-Sky Brightness	Photometric Night Fraction	2
Criteria 3	Sky Transparency	Night-Sky Brightness	3
Criteria 4	Altitude	Sky Transparency	4
Criteria 5	Seismic Vulnerability	Seismic Vulnerability	5
Criteria 6	Accessibility	Accessibility	6
Criteria 7	Wind Speed	Wind Speed	7
Criteria 8	Terrain Slope	Terrain Slope	8
Criteria 9	Landuse/Land Cover	Landuse/Land Cover	9

Table 4 Influence Weights for Evaluation Criteria

Evaluation Criteria	Preference Sequence 1	Preference Sequence 2	Influence Weights (AHP)
Criteria 1	Photometric Night Fraction	Altitude	0.307
Criteria 2	Night-Sky Brightness	Photometric Night Fraction	0.218
Criteria 3	Sky Transparency	Night-Sky Brightness	0.154
Criteria 4	Altitude	Sky Transparency	0.109
Criteria 5	Seismic Vulnerability	Seismic Vulnerability	0.076
Criteria 6	Accessibility	Accessibility	0.053
Criteria 7	Wind Speed	Wind Speed	0.037
Criteria 8	Terrain Slope	Terrain Slope	0.026
Criteria 9	Landuse/Land Cover	Landuse/Land Cover	0.019

homogenous and discreet classes for quantitative grading. For this purpose, the datasets are reclassified into desired number of classes (10) and suitability ranks are assigned to each class according to its suitability within the criterion. In reclassification, higher values are assigned to the class ranges that are more suitable for that particular decision problem and vice-versa. Whereas on the other hand, there are some class ranges that are not linearly favorable in ascending or descending order, rather certain ranges in a criterion map are appropriate for the decision problem. The factors that are linearly suitable for an optical-astronomical observatory in ascending or descending order are cloud frequency, aerosol concentration, terrain slope, distance from the road, distance from major fault zones, etc. On the other hand, factors like altitude and landuse / land cover have discrete favorable ranges for this decision problem.

5 RESULTS AND DISCUSSION

As a result of MCDA, we get two decision maps for the study with respect to both preferences (given in Table 3) that have been derived on the basis of brainstorming sessions with experts and with reference to previous astronomical site selection studies. Therefore, the results can be segregated into the following two cases:

5.1 Case 1

This case is based on the 1st order of preference sequence in which certain criteria – 'Photometric Night Fraction' and 'Sky Transparency' – have been preferred over 'Altitude'. Figure 10 demonstrates the potential areas according to 1st preference sequence, resolved through AHP.

According to the output of this method, a major portion along the areas of Nok Kundi, Chagai and Kalat appears to be the most suitable area for an optical-astronomical observatory, whereas the western half of Baluchistan Province is secondarily suitable. The result of this case identifies Baluchistan Province as the best potential area for optical astronomy. There can be two major reasons for the identified result of Case 1: (1) the area of Baluchistan is mainly arid because of low humidity

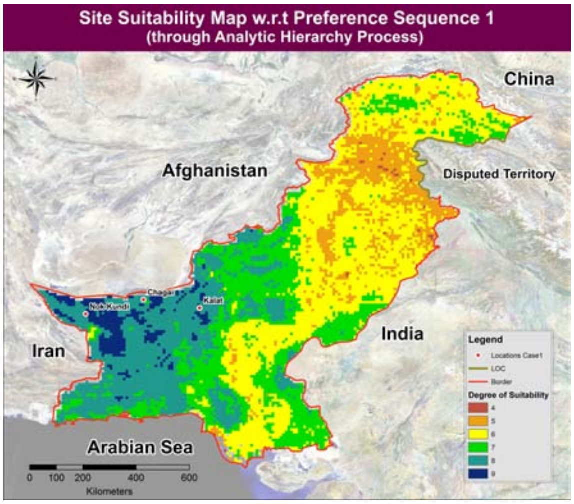

Fig. 10 Site suitability map with respect to preference sequence 1.

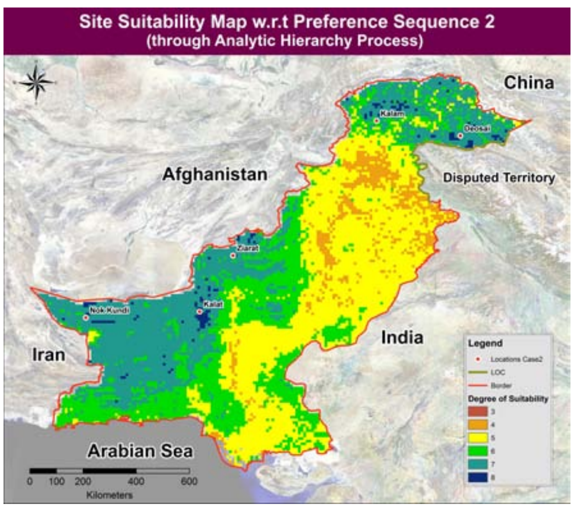

Fig. 11 Site suitability map with respect to preference sequence 2.

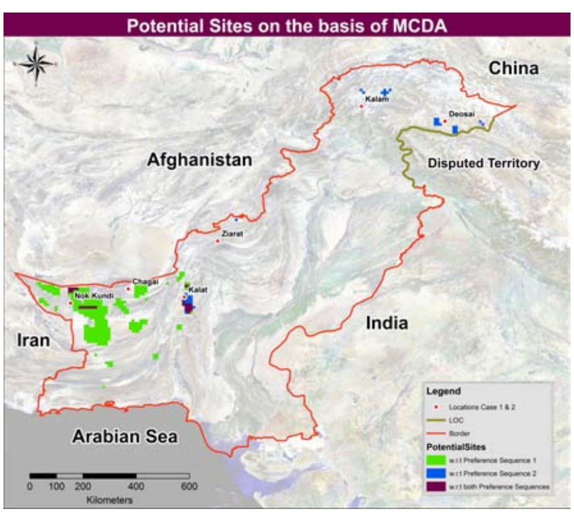

Fig. 12 Potential sites for astronomical observatory in Pakistan.

and cloud cover, making it suitable for optical astronomy; (2) on the other hand, the criterion 'Altitude' ranked 4th in this case, therefore, the ridges of Baluchistan that are moderately elevated are found to have better potential than the northern ranges of the country.

5.2 Case 2

This case comprises the MCDA process using the 2nd order of preference sequence in which criterion 'Altitude' has been preferred over the other astronomical and environmental aspects. Figure 11 exhibits the potential areas with respect to the 2nd preference sequence, resolved through AHP.

In the outcome of this arrangement, some of the areas around Nok Kundi, Kalat and Ziarat, Baluchistan; and some of the patches around Kalam, Kyberpukhtunkhawa and Deosai, Gilgit-Baltistan are among the best potential areas for locating an optical-astronomical observatory, whereas most of the area in Baluchistan Province and areas in the northern portion of the country are second in terms of favorability. The results of this combination seem accurate, especially for two sites: (1) firstly, the site of Kalat, Baluchistan was also recommended in one of the previous studies conducted by the Astronomy Division of the National Space Agency (Fawz-ul-Haq 1989); and (2) the site of Deosai has been internationally renowned for optical astronomy.

It is a common rule of thumb for optical astronomy that high altitude areas are commonly the most appropriate as several other requirements of optical astronomy get tuned with the rise in altitude. These requirements include low concentration of aerosols because of a thinner layer of atmosphere; low anthropogenic light pollution because of scarce human settlements; and appropriate landuse because of vacant land. Whereas, cloud cover and accessibility are the aspects that are against the high altitude areas of Pakistan because the areas remain overcast for a considerable part of year and the terrain of the area makes it difficult in terms of accessibility. However, in this result the high altitude areas are found to have more potential than the clear and cloud-free sky of Baluchistan Province because the areas might not be the best with respect to cloud clover and accessibility but they fulfill some of the most important requirements of optical astronomy that have already been mentioned above. Moreover, some excellent observations can be obtained from a site that is free from aerosols and anthropogenic light pollution, even if it provides a thin fringe of cloud free window for any part of a night.

With the intersection of both cases, there are at least two sites that have potential with respect to both preference sequences – the sites comprise the area near Kalat and a fringe beneath Nok Kundi (see Figure 12). Both of these sites are situated in Baluchistan Province over moderately elevated ridges with low aerosol concentration, anthropogenic light pollution and wind speed. The sites are easily accessible through a highway network and are considerably away from any active fault line.

6 FUTURE EXTENSION STUDY

Astronomical seeing is defined as the full width at half maximum (FWHM) of a stellar disc viewed at zenith with the wavelength of 0.5 m, using a telescope without adaptive optics, over a time span of 20–30 minutes and it is measured in arcseconds (Martinez et al. 2010). It is one of the most important aspects for ground-based optical astronomy that deals with blurring caused by variation in the refractive index of the air column through which the cosmos is observed. The blurring occurs because of air flow in various levels of the atmosphere that changes the refractive index of the medium and thus the optical path of light affects the wave-front coherence. Hypothetically, a site with good Sky Transparency (free from aerosols) would have a low value of astronomical seeing.

Even after acknowledging the importance of this criterion, it could not be included in MCDA because it is comprised of point based field data that are discrete in nature and could not be converted into raster-coverage. Therefore, the study does not cover the analysis for Astronomical Seeing. Whereas, the field observation for Astronomical Seeing specifically for the potential sites can further optimize the results.

There are some additional astronomical criteria, such as C_N^2 Parameter, Coherence Length, Coherence Time constant, Isoplanatic Angle, etc., that are used for a precise measurement of astronomical site selection. However, these parameters are vital for a large aperture telescope (30 m) that has sophisticated instrumental requirements. The inclusion of these parameters in future research will improve the research quality in various aspects of the field of astronomy.

This study covers terrain slope and seismic vulnerability but does not include other site selection criteria with respect to civil engineering construction protocols. Therefore, the study proposes large areas and selection of site can further be specified with the help of micro-level site selection analyses.

7 CONCLUSIONS

In this study we have investigated the optimal site for locating an optical-astronomical observatory in Pakistan. We selected nine evaluation criteria: namely Photometric Night Fraction; Night-time Sky Brightness; Sky Transparency; Aerosol Concentration; Altitude; Terrain Slope; Accessibility; Seismic Vulnerability; and Landuse/Land Cover. These criteria have been analyzed using MCDA and their influence weights have been calculated through the AHP method. In two of the studied cases (each based on a preference sequence/order of evaluation criteria), we identified potential sites: namely Deosai, Kalam, Kalat and Nok Kundi, whereas Kalat and a fringe near Nok Kundi were found to be the potential sites with respect to both preference sequences / orders. All of these sites are situated at high altitudes, with minimal aerosol and anthropogenic light pollution with sufficient number of cloud free nights. Therefore, these sites qualify for ground observation testing to locate the exact location of the observatory.

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