Mapping the Dark Sky Heritage: Spatial Modelling of Sky Brightness and Luminance for Pusat Astronomi Borneo in Sarawak, Malaysia

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Mapping the Dark Sky Heritage: Spatial Modelling of Sky Brightness and Luminance for Pusat Astronomi Borneo in Sarawak, Malaysia.

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Abstract: *The light pollution poses severe constraints to the observatory activities in scantily discovered places such as Sarawak, Malaysia, which needs assessment and scientific research in terms of multi-brightness analysis with astronomy spatial mapping considering cultural factors like New Crescent Moon sighting. This research intends to assess the levels of sky brightness and luminance at Pusat Astronomi Borneo (PAB), Santubong by measuring the brightness of the sky and spatially with Inverse Distance Weighting Interpolation in Geographic Information System. With the tool of the Sky Quality Meter, field measurements were taken for 31 sites point, from which the luminance values were computed from the sky brightness value. Specifically, the Stesen Hilal Teluk Bandung and Hujung Kuala were found to have the most significant conditions for astronomy and New Cresent Moon sighting due to the brightness and low light values below* 2.0×10^{-4} *cd/m²* *with mag/arcsec²* *greater than 21.3. The hypothesis was confirmed with the model inverse Pearson correlation of* $r = -0.992$*. These results aid in the long-term strategic planning by Sarawak Government and Sarawak Mufti Department in related to the conservation of dark-sky regions for scientific as well as Islamic purposes. The findings form a basis for policies regarding the development of observatories and light pollution control.*

Keywords: Light Pollution, Sky Quality Meter, Site Testing, Brightness Metrix, Geographic Information System.

1. INTRODUCTION

The expansion of artificial lighting on a regional scale, covering all aspects of economic and industrial activity, has escalated at a startling rate over the past few years. This new form of light pollution (LP) is escalating as a crucial restraint in the observation of astronomy, in particular, for ground-based optical observatory [1][2]. The night sky, essential for astronomical activities, is continuously getting overpowered by excessive LP leading to destruction and deterioration of astronomical data. Restoration of dark-sky site that are crucial for scientific research, education and heritage are a common problem faced by Malaysia like other countries [3][4]. Awareness is increasing but lack of systematic site assessments inhibits the effective identification and conservation of areas ideally suited for observatories and astrotourism. To fill this gap, this research aims Pusat Astronomi Borneo (PAB) in Santubong as shown in Fig 1, Sarawak as a location reserved for a national observatory because of its geographic seclusion from urban areas that emit the LP. This study aims to evaluate the optical PAB's capabilities through measuring sky brightness and luminance, by providing scientific evidence to support the claim. Through observational data from the Sky Quality Meter (SQM) and calculated candela (cd/m²) values, this work applies Geographic Information System (GIS) techniques to create spatial models of brightness metrics over the area of interest [5][6]. Findings will aid in the protection of dark sky site and improve the overall strategy for developing astro-tourism in Malaysia generally and Sarawak to be scientifically. This study offers unique novel contributions. This is the first spatial based sky brightness and luminance assessment for Santubong, Sarawak. The combination of SQM data with GIS based interpolation offers a new approach towards identifying core dark-sky zones. Furthermore, the transforming of the astronomical sky brightness into luminance candelas offers useful information to engineer while the associations to New Cresent Moon observations that add value for Islamic Calendar time keeping. These factors in combination make this study relevant from the scientific, environmental and religious perspectives.

2. METHODOLOGY

The evaluation of the optical site feasibility of Pusat Astronomi Borneo (PAB) involves field based sky measurements, photometric and statistical transformations, matrix classification, and geospatial modelling. The methodology is organized into six primary stages as follows below.

2.1 Pusat Astronomi Borneo, Santubong, Sarawak

The Pusat Astronomi Borneo (PAB) is located in Santubong, Sarawak, Malaysia, about 35 kilometers north of Kuching. Astronomical observations are made at the site because of its relative isolation from major urban centers, low population density and forested coastal zone which is Sarawak Geo-Delta. Such features would make PAB ideal to meet the requirements of dark-sky site and as a scope national observatory infrastructure. The study was carried out in the Santubong region where 31 observation site points were chosen according to the accessibility of the roads for each grid segment as shown in Fig. 2. All points were marked with latitude and longitude coordinates, which enabled spatial positioning and remote sensing surveying. One of the site points is Stesen Hilal Teluk Bandong, which at the moment as a temporary observation site until the completion of the PAB. PAB as the name suggests is a project under the Sarawak State Government and Jabatan Mufti Sarawak which aims enhancing the awareness for the astronomy research in moon sighting and space science.

Fig. 1. Latest design suggestion for Pusat Astronomi Borneo in Sarawak.

This initiative is in cooperation with the state and federal government such as the Sarawak Mufti Department (JMS), Sarawak Public Works Department (JKR), Sarawak Land & Survey Department (Land Survey), Department of Survey and Mapping Malaysia (JUPEM) and the Economic Planning Unit of the Premier Sarawak Department [6].

Fig. 2. Study area at suggestion site for Pusat Astronomi Borneo, Santubong, Sarawak.

2.2 Sky Brightness Measurement Using SQM

Sky brightness data was collected using the Sky Quality Meter-LU-DL (SQM), a photometric device calibrated to record sky brightness in magnitudes per square arcsecond (mag/arcsec²). The device was oriented vertically to capture zenith measurements and maintained a fixed field of view (FOV) of approximately 20° full width at half maximum (FWHM) as shown in Fig 3 [7]. Data was collected from 31 site points throughout PAB during cloudless and moonless nights to minimize interference from atmospheric scattering or moon illumination [8]. Each observation point was recorded using a GPS and labeled with time, date and location attributes.

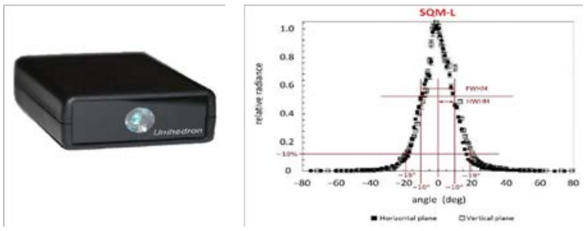

Fig. 3. Image of SQM-L unit (left) and manufacturer's declared calibration curve (right).

2.3 Calculation to Luminance

In order to compare the collected data with standards set for visual and engineering lighting, the values representing brightness of the sky, measured in mag/arcsec², were transformed into luminance in candela per square meter (cd/m²) with the following logarithmic expression:

$$L=10.8\times10^{(4.316-0.4\times SB)}$$

The SQM device is measured in mag/arcsec² and coded as Sky Brightness (SB) whereas the output luminous intensity in cd/m² is referred to as L. Additionally, 10.8, like most constants in the equation, stems from standard astronomical conversion determinants, in this case, it concerns the luminance of a uniformly the "bright sky". As for equation constants, 4.316 denotes reference brightness baseline, -0.4 indicates the change from logarithmic stellar magnitudes to linear luminance scale and 10.8 as stated earlier still pertains to the uniform sky luminance[9][10].

This equation was computed for every 31 rounded observational points, allowing for a fixed value estimate of the height dependence on the light stratum. These calculations make it possible to appreciate the level of light pollution existing at each site and to identify true dark sky reserves which serve as optimal sites for astronomical photometric surveys. Approximately redacting low cd/m² signifies quiet regions by the artificial light, making them the ideal scenario for astronomical observations, while stronger readings indicate the existence of sky glow [11][12].

2.3 Pearson Correlation for Sky Brightness and Luminance

In an attempt to evaluate the magnitude of the sky luminosity and the light from the background, the direct Pearson correlation coefficient was calculated using the raw SB data grouped with their corresponding values of luminance (cd/m²). The formula used is:

$$r = \frac{[n(\sum xy) - (\sum x)(\sum y)]}{\sqrt{([n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}$$

Within the boundaries of this study, x signifies sky brightness (SB), y represents the value of luminance and n indicates the number of features which in this case is 31. The variables $\sum xy$, $\sum x$, $\sum y$, $\sum x^2$ and $\sum y^2$ are the sums of the products while the respective squares that are needed for the correlation calculation. Conversion process defines both the consistent and the reliability of the graph which is shown to the right was verified using this statistical method. As predicted, the Pearson coefficient was strongly negative ($r < -0.9$). This cements that brighter skies (lower SB values) strongly correlate with higher luminance levels, while darker skies (higher SB values) produce much lower luminance. This step verified the photometric relationship, which is described in observational versus derived data and validated the further application of luminance in classification and spatial mapping.

2.5 Matrix Development: Sky Brightness vs. Luminance

A classification matrix was developed to cross-analyze each observation point's sky brightness and luminance values. This matrix used threshold values derived from international dark-sky guidelines to assign qualitative categories to each site. For instance, points with sky brightness greater than 21.75 mag/arcsec² and luminance below 0.00015 cd/m² were classified as "Excellent Dark-Sky Site," while those with brightness below 20.50 mag/arcsec² were categorized under "Suburban Sky." This matrix served both as a decision-support tool and as a reference for spatial modeling, making it easier to interpret the suitability of various zones briefly.

2.6 GIS Spatial Modelling

With the intention of PAB, GIS analysis was conducted using ArcGIS software to assess the spatial distribution of the darkness. To generate continuous surface maps of sky brightness and luminance, the Inverse Distance Weighting (IDW) interpolation approach was applied. The IDW formula used in this study is:

$$Z(x_0) = \frac{\sum_{i=1}^{n} \frac{Z(x_i)}{d(x_0, x_i)^p}}{\sum_{i=1}^{n} \frac{1}{d(x_0, x_i)^p}}$$

In this context, $Z(x_0)$ is the unsampled output to be retrieved and $Z(x_i)$ is the output at sampled or observed points. Also $d(x_0, x_i\})$ refers to the distance to the prediction location and each known data point in the framework of spatial data analysis. The power p in the weighting function (set to 2 in this case) changes the influence that each measurement has on the prediction, whereby closer points have a stronger influence [13]. With this formula, both sky brightness and luminance values were interpolated over the entire PAB region. The maps generated exhibited zones of optimal dark-sky conditions along with areas of light pollution. The maps then were combined with topographic maps to analyze their spatial relevance concerning the terrain and sources of artificial illumination, aiding in the assessment of the site's suitability regarding prospective light pollution.

3. RESULT AND DISCUSSION

This chapter presents the findings from the sky brightness and luminance study conducted at Pusat Astronomi Borneo, Sarawak. The data was collected from 31 locations to examine the magnitude of light pollution in the area. A Sky Quality Meter was used to measure the sky brightness which was also converted to luminance for comparative purposes. The results show observed and predicted values alongside GIS mapping also the correlation of brightness and luminance. To facilitate clear understanding of the results, charts tables, and maps were utilized. This chapter attends to the identification of the best areas relative to the darkest zones as established in the study for constructing observatories or engaging in astronomy related endeavors.

3.1 Sky Brightness and Luminance Distribution

Table 1. Observed and predicted values of sky brightness and luminance at selected five site in PAB.

Site Point Station	SB_Obs (mag/arcsec²)	SB_Pre (mag/arcsec²)	Candela_Obs (cd/m²)	Candela_Pre (cd/m²)
Hujung Kuala	21.59	21.55	1.5×10^{-4}	1.6×10^{-4}
Teluk Bandung Hilal	21.53	21.5	1.6×10^{-4}	1.7×10^{-4}
Kpg. Budaya	20.51	20.6	7.1×10^{-4}	6.9×10^{-4}
Kg. Buntal	20.88	20.9	4.7×10^{-4}	4.5×10^{-4}
Dlm. Kampong	21.0	21.05	3.9×10^{-4}	3.8×10^{-4}

At Santubong, 31 site points within the proposed site of PAB have their sky brightness measured using a SQM-LU-DL. This instrument measures the darkness of the night sky in terms of magnitudes per square arcsecond (mag/arcsec²), which is an accepted astronomical measure of the condition of a night sky. The studied area managed to maintain sky brightness values between 20.51 and 21.59 mag/arcsec² during moonless night. These values were further transformed into photometric cd/m² and transformed for engineering comparison, allowing evaluation against illumination standards as well as visual perception thresholds. Based on Table 1, the values of 1.5×10^{-4} cd/m² and 7.1×10^{-4} cd/m² are recorded at Hujung Kuala and Kpg Budaya respectively. This illustrates the degradation and variations of light pollution across the site points. These readings show the vast difference between fully shielded dark zones & regions surrounded with artificial light sources like roadside lights & nearby human habitation. The comparison shows a very good match between the predicted and observed data. For example, Hujung Kuala, one of the darkest stations in the grid, showed a sky brightness of 21.59 mag/arcsec² (observed) and 21.55 mag/arcsec² (predicted).

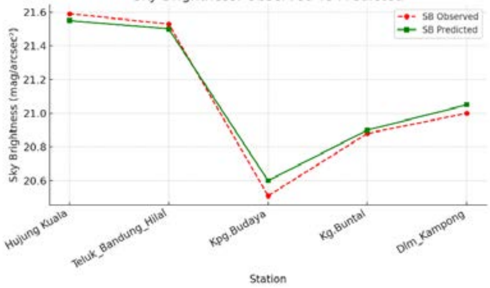

Fig. 4. Sky brightness (mag/arcsec²) observed and predicted values across selected stations.

Its corresponding luminance was 1.5 × 10^{-4} cd/m² (observed) and 1.6 × 10^{-4} cd/m² (predicted). At Teluk Bandung Hilal, the observed values were 21.53 and 21.50 (brightness) and 1.6 × 10^{-4} and 1.7 × 10^{-4} cd/m² (luminance). Even in more light-polluted locations like Kpg Budaya, the discrepancy in observations and predictions was very low; for example, 0.09 mag/arcsec² for brightness and 0.2 × 10^{-4} cd/m² for luminance. These comparisons were shown in two charts. In the first chart, the trend of sky brightness for all five stations was captured and the observed data is shown in red while predicted values are in green. Both lines are parallel, indicating that the predicted values sufficiently capture the measured variations from the field. The second chart uses the same format to compare candela photometric units with the second axis of the chart labeled as luminance. Once again, predicted data closely follow observed data, indicating that the fidelity of the photometric modelling process is high. This accuracy supports confidence in theories that spatially interpolated data can be used to determine appropriate locations suitable for astronomical activities. The accuracy of the predictions is particularly important in the case of Stesen Hilal Teluk Bandung and Hujung Kuala, especially when planning the infrastructure for observation, dome positioning and strategies for preserving dark-sky areas. The spatial model's accuracy in depicting the natural sky brightness attests to how helpful it is as a support tool for astronomy site evaluations and astrotourism development in Sarawak.

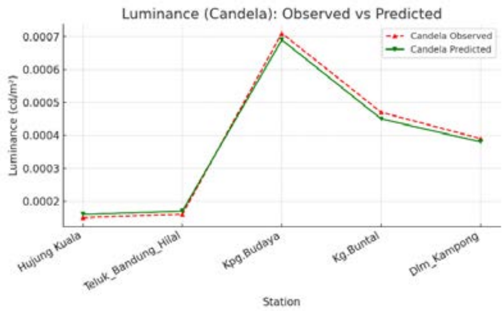

Fig. 5. Luminance (cd/m²) observed and predicted values across selected stations.

3.2 Pearson Correlation Analysis

In order to validate the relationship between the sky brightness and luminance, Pearson correlation analysis was performed on both the observed and predicted datasets. For the case of observed sky brightness, the correlation with observed candela yielded r = -0.992.

Table 3. Pearson correlation values between observed and predicted sky brightness and luminance.

Variable 1	Variable 2	Pearson r
SB_Obs	SB_Pred	0.999
Candela_Obs	Candela_ Pred	-0.992
SB_Obs	Candela_Obs	-0.992
SB_Pred	Candela_Pred	0.999

In order to validate the relationship between the sky brightness and luminance, Pearson correlation analysis was performed on both the observed and predicted datasets. For the case of observed sky brightness, the correlation with observed candela yielded r = -0.992. This very strong inverse relationship suggests that as one value increases, the other decreases significantly. Predicted data was also in close agreement with observed data, as indicated by the correlation of r = -0.989. A heat map was created to show these associations. In the detailed correlation heatmap, a complete symmetric matrix was constructed from the observed and predicted values of sky brightness and candela to encapsulate all possible pairings. The correlation between observed and predicted sky brightness was r= 0.999, signifying a almost perfect correlation. The same outcome was noted for the observed and predicted candela values where r was also 0.9997, demonstrating high accuracy and consistency with the data modeling. Additionally, correlations such as SB Obs with Candela Pred (r = -0.989) and SB Pred with Candela Obs (r = -0.992) also displayed strong negative relationships, indicating reliability. The comprehensive heatmap portrays both calculations which are consistent with the values provided and measured, ensuring confidence when performing evaluations and modeling at a site.

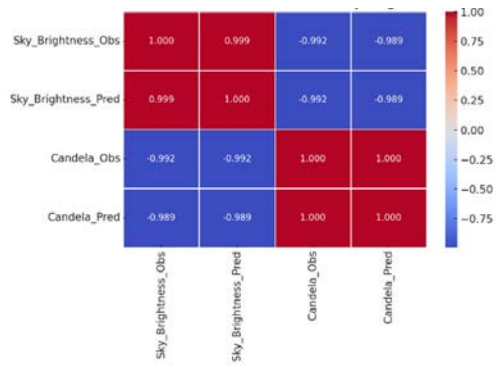

Fig. 6. Correlation between observed and predicted sky brightness and luminance values.

3.3 Spatial Modelling Using GIS

The spatial model comparison using observed sky brightness data for the PAB area and the predicted sky brightness data. The observed map used in this analysis is contained in the measured sky brightness map, which was created using 31 site points collected with the SQM device. Based on the obtained map, the observation area illustrates the northwest region of PAB surpassing Stesen Hilal Teluk Bandung and Hujung Kuala are under the darkest skies that have sky brightness values above 21.3 mag/arcsec². The values denote excellent conditions for astronomy and light pollution. Southern and eastern areas including Kg.Buntal and Dlm_Kampong along with Bulatan Polis display below 21.0 mag/arcsec contributing to lower sky brightness which indicates elevated illumination from surrounding villages roads and tourist hotspots. The predicted sky brightness map is precise to the data pattern from the light pollution map, retaining consistency in dark and bright zones with low differences in transition areas. This affirms that the model can accurately predict sky brightness in areas for the astronomy observation activity. In general, this figure demonstrates that the GIS model accurately tracks sky brightness over the entire area of study. It assists in determining optimum locations for observatory construction, as well as areas that need protection from light pollution, particularly in the core dark sky regions located in the northwest part of PAB.

While the observed values for luminance (candela) were calculated using a photometric formula to field measured were generated using GIS based IDW interpolation. In the observed map, the darkest areas northwest region continues to remain as the lowest bounded near Hujung Kuala and Stesen Hilal Teluk Bandung where the ranges of cd/m² lumance value is still mostly less than 2.0×10^{-4}. These values show places where artificial light is good and the conditions are suitable for astronomical observation. However higher luminance levels appear at Kg Buntal, Bulatan Polis and Spg Binyuk at southeastern which possess lower than 6.0×10^{-4} cd/m² demonstrating greater susceptibility to surrounding light pollution from roads, villages and tourism areas. The predicted luminance map demonstrates rough similar to the spatial trend, dark zones and bright zones still mostly aligned with the observed pattern, with few notable imperfections at border areas the to pinpoint all major data and low luminance regions.

By looking at both Figure 6 (sky brightness) and Figure 7 (luminance), the northwest area of PAB is the best location for astronomy. Places like Stesen Hilal Teluk Bandung and Hujung Kuala have the darkest skies and the lowest candela values, which means they are least affected by light pollution. These areas are suitable for setting up observatories, telescopes, and conducting moon sighting (rukyah hilal). On the other hand, places like Kg.Buntal, Bulatan Polis and Waterfront show brighter skies and higher luminance, so they are less suitable due to nearby lights from roads and villages.
This consistent pattern in both models helps clearly identify the most suitable and least disturbed zones for astronomical activities at PAB.

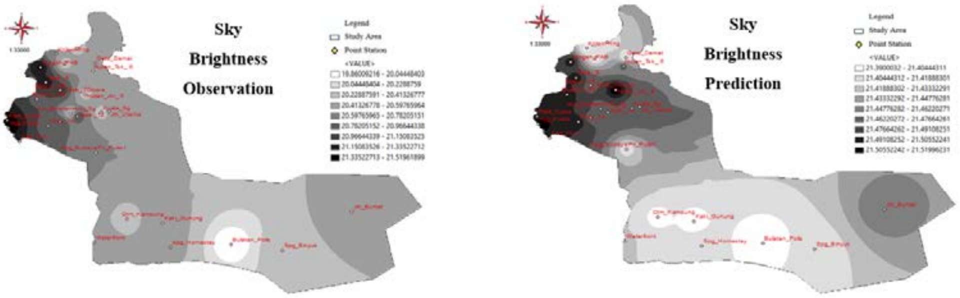

Fig. 7. Comparison Spatial Model at site selection for PAB between sky brightness observations data and predictions data.

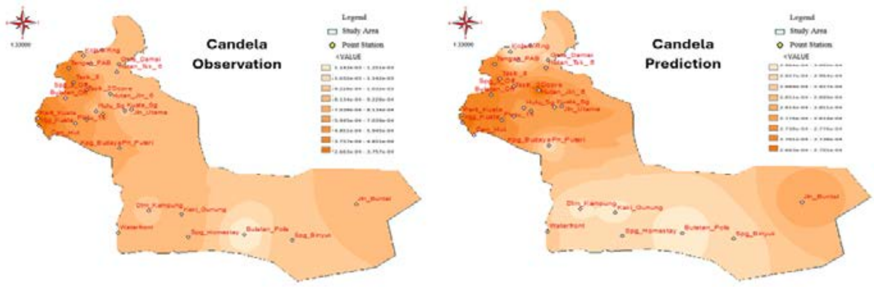

Fig. 8. Comparison Spatial Model at site selection for PAB between Candela observations data and predictions data.

3.4 Sources of Light Pollution and Impacts on New Crescent Moon Visibility

In this study, a key factor is the finding of local sources of light pollution, not only with regards to the general astronomical observations, but also the sighting of the new crescent moon, which is pivotal of Hijri months in an Islamic calendar. Based on the map, the most significant contributors are coastal and road lightening systems consisting of streetlights, both high pressure sodium and LED installed on access roads to popular beaches like Damai Beach. Moreover, lighting for tourism-based activities strongly supports constant skyglow due to external decorative lights from resorts and beach. Also, residential areas like Kampung Santubong contribute to upward light sky glow[14]. Light emissions from marine activities alongside sea areas add to the scattered light on the horizon, especially during nighttime vessels or activities in the harbor[15]. The zenith measurements taken at PAB verifying that the sky is adequately dark for astronomy since values of sky brightness surpass 21.5 mag/arcsec² in multiple zones, which difference between 0.3 to 0.6 mag/arcsec², has clear consequences on crescent moon visibility. Rukyah hilal is highly responsive to such low-light contrast conditions around the western horizon right after sunset[16]. In such cases, even a small amount of light pollution poses a threat to the visibility of the crescent. These results emphasize the relationship concerning reliability of rukyah hilal and localized light pollution. Secondary reason deals with shorter periods of moon observation which leads to more reliance on telescope devices. Hence, it is suggested that the proposed construction of PAB includes light shielding plans and preservation for secure the activity either in religious matter or focus astronomical research in the future.

4.0 Conclusion

This study has revealed that the northwest region of Pusat Astronomi Borneo particularly Stesen Hilal Teluk Bandung and Hujung Kuala has the darkest skies within the area. This site points are most appropriate for astronomy activities, New Crescent Moon sighting and development of observatories. The comparison between the observed values and those predicted values of sky brightness and luminance showed very strong correlation which validates the assumption made in this study proving the prediction model is indeed reliable and useful in mapping dark sky areas [17,18]. As a conclusion, local authorities and policymakers are advised to preserve these dark sky regions by controlling the amount of light used outdoors especially around villages and near tourist sites. Certain lighting policies including the use of shielded lights and reduction of brightness caps should be set in place. Additionally, PAB should be touted as the official dark sky site and astronomy location of interest in Sarawak. The uniqueness of this study novelty is in the fusion of scientific inquiry and religious that connecting light pollution study with Islamic New Crescent Moon sightings in astrotourism development. Its mixed approach of combining observational and predictive data, as well as converting sky brightness into actual light measurement units, is useful for engineering and ecological policy makers. These findings will help form policies to restrict light pollution in Malaysia and other regions especially in Sarawak.

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