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Dynamic Assessment of Urban Carrying Capacity Load Number Using the Enhanced UCCLN Model

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Abstract: The sustainability of cities often changes as rapid urban developments and population growth affect the carrying capacity. Understanding the dynamics of carrying capacity then becomes crucial for tourist-oriented cities. This study focused on Baguio City, the "Summer Capital of the Philippines," attracting large crowds on holidays and actively promoting various events on non-holidays, thereby having temporal context variations classified as regular days, days with events, and holidays. Using the enhanced urban carrying capacity load number (EUCCLN) model, load number (LN) changes for different temporal contexts are calculated based on spatial indicators grouped into air, traffic, economy, and waste. The city experiences the worst pressures on air quality during holidays with 99.23% districts under very high to critical levels followed by regular and days with events. However, the total LN is balanced by favorable economic conditions with only 9.23% at critical. EUCCLN effectively pinpoints areas experiencing critical states at any time, advocating targeted government monitoring. We demonstrate that Night Time Light, for places with no economic data available, can be used as a proxy to highlight areas requiring improved urban vibrancy. This work suggests that EUCCLN monitoring urban pressures can easily be expanded to nowcasting with real-time data.

Keywords: enhanced urban carrying capacity load number (EUCCLN) model; load number; dynamic impact assessment; urban carrying capacity; Baguio City

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1. Introduction

The rapid pace of globalization and economic growth has brought urban development to the forefront, necessitating a paradigm shift towards sustainability in urban settlements [1–3]. Sustainability in this context encompasses thoughtful consideration of Environmental, Social, and Governance (ESG) elements and examines various components of demographic, environmental, social, economic, transportation, and ecologic features of an area [4–6], acknowledging their intricate interplay and their far-reaching impact on the urban ecosystem in both short and long-term horizons. Ultimately, sustainability in urban development aims to create livable and friendly places that are not only habitable but also nurturing for current and future generations. This pursuit aligns with the Sustainable Development Goals (SDGs) of the United Nations that recognize cities to be centers of innovation and hubs of growth, underscoring the imperative to make them sustainable, inclusive, safe, and resilient [7].

In response to the call for action on the Sustainable Development Goals, there has been a growing demand for initiatives that advance sustainable cities' planning, management, and capacity-building. The urgency comes from the realization that urban ecosystems are vulnerable to irrevocable damage, particularly from challenges such as pollution, resource depletion, and overconsumption, when the pressures exerted on them exceed their inherent capacities [1,3,8]. Within this context, the Urban Carrying Capacity (UCC) concept emerges as an essential metric, offering thresholds that delineate the limits of human activities, population growth, per capita consumption, waste production,

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land utilization, and physical infrastructure development before urban ecosystems reach potential devastation [1–3,9–13].

Several descriptive-analytical and numerical models have been introduced in the past few years to measure UCC. These methods typically involve the selection of indicators and their categories, the evaluation of the limits of indicators, and the calculation of their weights or relative contribution to UCC. Wei et al. [10] proposed using Mean-Variance Analysis to determine the weight of each of their chosen indicators based on five categories of variables: economic, resources, environmental, infrastructure, and transportation. They further evaluated the comprehensive UCC conditions of megacities and determined that environmental and infrastructural aspects, followed by resources, economic factors, and transportation, contribute the most to UCC. To incorporate the ecological dimension of an urban ecosystem in the selection of indicators, Irankhani et al. [14] proposed the use of Geographic Information System Fuzzy Modeling (GISFM) in gradating the carrying capacities of the ecological indicators according to the maximum accepted and desirable limits. Combined with the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) method in identifying the limits of socioeconomic indicators, they showed that no districts in Shemiran City, Tehran, Iran had desirable UCCs. The selection of their indicators was based on the Driving forces-Pressures-States-Impacts-Responses (DPSIR) framework, which describes interactions and causal relationships between human activities and the environment [5,14]. Esfandi and Nourian [9] also assessed the UCC of Tehran's districts in the context of the development of mega malls based on economic, social, environmental, and traffic indices in their proposed UCC Assessment Framework (UCCAF), which calculates the Degree of Carrying Capacity (DCC) of each district in relation to each indicator. DCC consists of 6 categories that are utilized in evaluating the pressure of the indicators from desirable to critical level (see Table 5) [3,15]. Their results revealed that some districts have very poor carrying capacity levels for mega malls and that site selection for mall construction neglected urban planning principles. Li et al. [13] proposed a "Pressure-Capacity-Potential" framework to calculate Urban Comprehensive Carrying Capacity (UCCC) using multifactor weighted summation, graded assignment, stepwise correction, and subsection variable weight. Their framework evaluates the urban carrying pressure, capacity, and potential indices based on their particular indicators, which are then used to calculate the UCCC of an area. The researchers identified three (priority, key, moderate) development zones from the calculated UCCC which have their own recommended actions for sustainable urban development.

Recently, Tehrani et al. [1] proposed the Enhanced Urban Carrying Capacity Load Number (EUCCLN) model as an improvement to the Urban Carrying Capacity Load Number (UCCLN) model [2,3]. Both models use weighted indicators and DCCs to calculate the study area load numbers (LNs), which represent the combined impact from the pressure that an indicator places on an urban ecosystem based on DCC and the perceived importance of that indicator by experts. Although the UCCLN model aims to estimate the UCC of an area based on indicators in the contracted DPSIR framework called Pressures-States-Impacts-Responses (PSIR), the EUCCLN model focuses on monitoring human-induced impacts and thus only uses human impact indicators. It also integrates remote sensing and Geographic Information System (GIS) for better data management and monitoring. With this simplification, the authors concluded that impact pressures alone, such as waste production, air pollution, and traffic congestion, can cause irreversible damage to the urban ecosystem [1].

The urban economic, social, and environmental criteria comprise a holistic description of sustainable urban development [4], which can then be used as indicators to calculate the UCCLN. Some studies also indicate the addition of infrastructure and transportation as separate criteria for the assessment of carrying capacity indices [9,10]. Examples of indicators that characterize the socio-environmental conditions of an area are waste production and air pollution indicators, while traffic congestion is an example indicator that characterizes transportation. The impact indicators that the EUCCLN model used are not related to the urban economy [1].

Although prior research [1–3,5,8–10,14,16] was proven to be useful in assessing the UCC of an area, rapid urban development, tourism-related activities, and population growth make the UCC very dynamic, implying the need for it to be recalculated for various temporal contexts, such as for regular days, for holidays, and during weather-related disturbances. This dynamicity was previously recognized by several works [8,43]. Wang et al. [8] when they conducted dynamic assessments of the Tourism Carrying Capacity (TCC) of some of the top Chinese urban tourism destinations. They evaluated their TCC under various simulation scenarios based on the focus of different policies, which highlighted the significant role of environmental management strategies for TCC. Although this study explored different scenarios, thereby exhibiting the dynamicity of TCC, it overlooked daily fluctuations. Zhang et al. [17] also used TCC to monitor the impact of visitor attendance in theme parks and distinguished between busy and non-busy days, noting its influence on visitor experiences, satisfaction, and behavioral intentions. While the TCC provides thorough attention to the conditions in tourist hotspot settlements, calculating the TCC requires extensive tourism data from the study area, which may not be available to developing countries. A notable research gap lies in the exploration of advanced techniques, particularly the utilization of satellite data, to improve the precision and efficiency of UCC and TCC assessments.

Nighttime light (NTL) intensity data, collected by satellites, is publicly available daily data that provides a unique way to track urban growth. These data show us where and how people use artificial light at night, revealing human activity or urban vibrancy in cities and communities. Studies suggest the use of Nighttime Light (NTL) data to effectively capture urban activity [18–21]. NTL can be used as a proxy for urbanization within a city, as it exhibits a robust correlation with socioeconomic factors, making it well-suited for modeling and monitoring spatial variables [21]. This aids in understanding temporal and spatial patterns of socioeconomic activities that are crucial for developing sustainable strategies for urban planning.

This work focuses on Baguio City, Philippines, a city that has a unique position as both a highly urbanized center and a tourist hotspot: it is known to be the "Summer Capital" of the Philippines[22]. The city's local festivals and special events attract tens of thousands of tourists, far surpassing the regular influx on typical days [23]. However, this surge in tourism and population movement has brought significant challenges to the city. Traffic congestion is a prevalent problem, especially during peak seasons and holidays, leading to inconveniences and increased air pollution due to congested narrow roads and the resulting delays. In addition, the increase in tourists strains waste management systems, resulting in higher waste generation from hotels and restaurants. Therefore, the UCC load number is expected to be dynamic for this city, and even its local government [24] has recognized the need to regularly measure UCC and use it as a basis to develop customized solutions that can support and maintain tourism activities.

This paper measures the UCCLN of Baguio City using the EUCCLN model updated with an economic indicator and contextualized on varying days. Due to the lack of data on economic indicators for the city's districts, NTL is used as a proxy indicator of economic activity and urban vibrancy. This study extends the EUCCLN model to incorporate economic indicators through NTL data as a proxy indicator of economic activity or urban vibrancy. Using this extended model, the changes in load number for various temporal contexts are investigated. The resulting insights into the dynamics of UCCLN are especially useful in assessing the pressures in highly urbanized tourist hotspots, where LN is highly fluctuating. The same framework can then be applied to less urbanized tourist hotspots or urbanized cities that are not tourist hotspots.

2. Materials and Methods

2.1. Study Area

Baguio City, often known as "Baguio," is an attractive mountain city nestled in the Cordillera mountain range on the island of Luzon. It is positioned approximately 270 kilometers north of Manila, the capital of the Philippines, at an elevation that varies between 900 and 1,600 meters above sea level [25]. Classified as a highly urbanized city within the CAR (Cordillera Administrative Region), Baguio consists of 129 smaller administrative divisions known as *barangays*, which is analogous to *districts* in other cities and covers a land area spanning 57 square kilometers. According to the Philippine Census of Population and Households 2020 [26], it has an urban population of 366,358. The high altitude of Baguio contributes to its pleasantly cool climate. In contrast to most of the country, which has a tropical climate, Baguio enjoys a subtropical highland climate characterized by consistently lower temperatures throughout the year. Additionally, the city boasts more than 50 tourist attractions exhibiting distinct historical, cultural, religious, scenic natural geographic features and man-made leisure areas. These favorable climatic attributes and diverse tourist attractions make Baguio an attractive destination for residents and tourists seeking a break from the sweltering tropical heat.

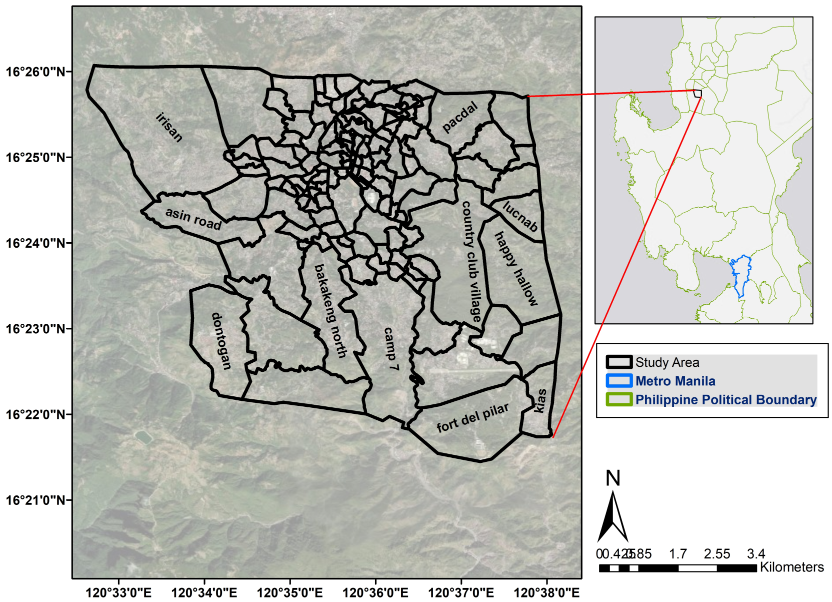

Figure 1. Administrative boundary of Baguio City.

2.2. Data

Similar to the impact indicators used in the EUCCLN model [1], which consisted of three criteria (*air quality*, *traffic*, *waste*), nine indicators were used in this study: six for air quality (average concentration of Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), particulate matter smaller than 2.5 μm ($PM_{2.5}$), particulate matter smaller than 10 μm (PM_{10})), two for traffic (intra-*barangay* trips and inter-*barangay* trips), and one for waste (waste generation). In addition to the three criteria, we also added *economic*, which used Nighttime light (NTL) intensity data as a proxy for GDP and economic activities. This brings the total number of indicators in our model to ten. When available, all data are geolocated to their corresponding *barangays*. Table 1 summarizes the indices used for each criterion and their corresponding spatial granularity.

The following sections discuss the details of temporal contexts, data collection and processing, the importance coefficient (IC), and the limits for each indicator's degree of carrying capacity (DCC). Finally, each criterion's load number (LN) calculation is also presented.

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Table 1. Different criteria with their corresponding indices that were considered for the Load Number (LN) calculation. Due to data availability, the spatial granularity is either at *barangay*-level or city-level.

Criteria	Indices	Spatial Granularity
Air Quality	$PM_{2.5}$, PM_{10}, CO, CO_2, NO_2, SO_2	*Barangay*-, City-level
Traffic	Intra-*barangay* trips, Inter-*barangay* trips	*Barangay*-level
Economy	NTL (GDP)	*Barangay*-level
Waste	Waste generation	City-level

2.2.1. Temporal Context Variation

The time series data in this study were divided into three categories of varying contexts: regular days, holidays, and days with events. Each category in Table 2 comprises twelve days chosen throughout the year 2023, including some days in December 2022.

Table 2. List of dates used for the different temporal context variations, based on the actual happening in Baguio City.

Regular days	Holidays	Days with events
January 13	April 2	January 22
January 14	April 3	January 27
January 15	April 4	January 29
January 16	April 5	March 6
January 17	April 6	March 13
January 18	April 7	March 20
January 19	April 8	March 24
June 19	April 9	March 25
June 20	April 10	March 26
June 21	December 23, 2022	March 27
June 22	December 24, 2022	September 8
June 23	December 25, 2022	September 9

The regular days were randomly chosen from a pool of non-holiday dates without locally organized events. Only dry days were considered since wet waste collected during rainy days increases their measured weight, which would then skew the data analyzed. In the Philippines, the rainy season runs from June to November, while the dry season runs from December to May [27]. The holidays included nationally mandated holidays such as the weeklong Holy Week from Palm Sunday on April 2 to Easter Sunday on April 9. April 10 was the Philippines' Day of Valor holiday, while the days in December included the weekend leading up to Christmas Day on December 25. The days with events column in Table 2 refer to locally organized events in Baguio. On January 22, 27, and 29 there were events to celebrate Chinese New Year in Baguio City. The listed days in March were events celebrating the *Panagbenga* Flower Festival and Strawberry Festival, while the listed days in September were events celebrating the Baguio Country Fair.

2.2.2. Air Quality

Air quality data was taken from three air quality sensors in the city's central area, where most tourists flock. These data were representative of the whole city, except for PM 2.5 and PM 10. Data for PM 2.5 and PM 10 were collected by placing 80 Atmotube Pro units in volunteers whose nature of work requires moving around the city at most times of the day. Each unit has an assigned device name and MAC address, which serves as a unique identifier for the device during pairing with a smartphone. The Atmotube Pro offers real-time detection of PM2.5/PM10 concentrations ($\mu g/m^3$) and latitude and longitude values every 10 minutes. Atmotube Pro is self-calibrating and is certified to have accurate and acceptable measures for PM 2.5 and PM 10, both in controlled settings and field

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tests [28]. The air quality data collected from each Atmotube Pro device were geolocated to their respective *barangays*, and the resolution was downsampled to the daily average. Here, the outliers for each *barangay*, defined to be data points greater than three standard deviations from the mean, were then removed [29]. Since not all places can be visited by volunteers, missing data was imputed with the daily average of neighboring *barangays* if available, otherwise, by the average of all *barangays*. With Atmotube Pro, the ambient air quality of each *barangay* can be detected.

2.2.3. Traffic

As part of a partnership with the Baguio City Local Government Unit, 500 GPS sensors were installed on public and private vehicles throughout the city, most (80%) of which are taxis, as probe vehicles in this study. Vehicle trip data collected includes vehicle speed, date, time, and longitude and latitude coordinates, which were geolocated. For each of the temporal variations described in Section 2.2.1 (events, holidays, regular), the average number of inter-*barangay* and intra-*barangay* trips within 100 m^2 were obtained from the daily origin-destination (OD) matrices normalized by the total area of the *barangays*.

2.2.4. Waste

The Solid Waste Management Division of the Baguio City General Services Office provided the daily waste collection report. The data provided include the total weights of the produced and recycled waste for each day for the city. The records show missing data on some regular days due to power outages and waste collection personnel holidays, and these were imputed with the average data under the same temporal context. In 2022, a waste analysis characterization study (WACS) was conducted to determine the average per capita solid waste generation (PCG), and it was found that the PCG in Baguio City was 0.49017 kg per person, including tourists. This is 22.54% higher than the average per capita generation rate for the Philippines [30], but 33.76% lower than the average per capita generation rate of the world [31].

2.2.5. Nighttime light (NTL)

The Black Marble VIIRS/NPP Gap-Filled Lunar BRDF-Adjusted Nighttime Lights dataset, provided by NASA's EOSDIS, is a high-quality global dataset of nighttime lights derived from observations made by the VIIRS instrument on the Suomi NPP satellite. It offers a spatial resolution of 500 meters and provides daily data, making it suitable for monitoring changes over short periods. The dataset has undergone processing steps, including BRDF adjustment, gap filling, and lunar correction, to enhance accuracy. Although it is considered one of the more accurate sources of global nighttime light data, factors such as cloud cover, atmospheric conditions, and local light pollution can still influence the accuracy of the data in specific regions or time frames [32]. This study downloaded and extracted NTL data for 2018-2023 in Baguio City. The HDF5 file format of NTL was converted to GeoTIFF using Python. The total intensity was geolocated considering the total areas of each intensity value given per *barangay*.

2.3. Importance Coefficients

The Importance Coefficient (IC) matrix is a framework for weighting indicators according to their importance in evaluating the UCC. In this work, seven experts in the fields of systems management, transportation development, city planning, tourism, smart city, and air quality were interviewed to determine the weights of each indicator chosen following the Analytical Hierarchy Process (AHP) [1,3]. This method is a multicriteria evaluation of quantitative and qualitative information that can be designed at two levels of hierarchy: criteria and subcriteria [33–35]. Experts were asked to complete questionnaires following Saaty's pairwise comparison table [1] as shown in Table 3.

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Table 3. Comparison matrix for the AHP indicator in the study.

Criteria/Sub-criteria	Indicator A	Indicator B	...	Indicator Z	**Priority Vector**
Indicator A					
Indicator B					
⋮					
Indicator Z					

Each row-wise criteria / sub-criteria in Table 3 is compared against the column-wise criteria / sub-criteria and scored in fixed values according to its relative importance to the other. These values are described in Table 4. Once the comparison table is filled out and checked for consistency [36], the overall weight of each indicator is taken as the Priority Vector (PV) calculated from the matrix's normalized eigenvector. To get the overall IC matrix, each sub-criterion indicator PV is multiplied by the criteria indicator PV it belongs.

Table 4. AHP scoring values and their corresponding description based on Tehrani et al. (2023) [1]

Relative Importance	Equal importance	Somewhat more important	Definitely more important	Much more important	Very much important
Value	1	3	5	7	9

2.4. *Degree of Carrying Capacity Indicators*

Each indicator's Degree of Carrying Capacity (DCC) is determined among six classes with corresponding interval levels particular to the indicator. This classification is widely used for UCC studies and is adopted from the Pressures-States-Impacts-Responses (PSIR) framework commonly used in environmental indicators. Each class represents a DCC value and a pressure degree. Previously accepted classifications for each indicator (e.g. air pollution) were applied, otherwise the values were equally divided into 6 classes. Table 5 presents the six classes and their characterization [1–3,15].

Table 5. Six classes of DCC and their characterization

Class	**1**	**2**	**3**	**4**	**5**	**6**
DCC (min-optimal)	**0.1**	**1**	**2**	**3**	**4**	**5**
DCC (max-optimal)	**5**	**4**	**3**	**2**	**1**	**0.1**
Pressure degree	Very low	Low	Medium	High	Very High	Critical
Meaning of indicator limits	Desirable level with no or minimal negative impact	Level with low negative impact	Level with medium negative impact	Level with high negative impact	Maximum acceptable level without irreparable damage (threshold level)	Critical level with possible irreparable damages

The range of values for each class of $PM_{2.5}$ and PM_{10} follows the World Health Organization (WHO) guidelines [37] in terms of the values of minimum desirable limit and maximum acceptable limit, and are constant for all variations in the temporal context. Meanwhile, the DCC of the average concentration for CO, CO_2, NO_2, and SO_2, intra-*barangay* and inter-*barangay* trips, NTL intensity, and waste were considered based on equal intervals of their values [9,15] from the raw data. As a pioneering study for Baguio City, there is a lack of knowledge on the minimum desirable limits and maximum acceptable limits for these indicators. Note that the raw data for $PM_{2.5}$, PM_{10}, intra-*barangay* trips, inter-*barangay* trips, and NTL intensity were distinguished by *barangay*, whereas the CO, CO_2, NO_2, SO_2, and waste indicators were classified for the whole city, mainly due to data availability. Given the lack of previous studies on the thresholds of indicators for Baguio City, the DCC limits for each of the different temporal contexts were calculated separately with the goal of investigating the fluctuations of DCC levels in each of the time periods.

2.5. Load Number Calculation

The Load Number (LN) of an indicator represents the pressure the indicator places on an urban ecosystem based on the degree of carrying capacity and the importance of that indicator [1–3]. It is the product of its DCC and its IC,

$$LN = DCC \times IC. \quad (1)$$

In this work, we calculate the LN of each indicator for each *barangay* for different temporal contexts.

3. Results

This section is organized starting with the presentation of the importance coefficients (IC), followed by the calculated DCCs, and finally the visualization of LNs for different temporal contexts. Although the main goal of this work is to present how the impacts of indicators (LNs) change for different temporal contexts, we first present the distribution of the different DCC levels for the entire city to understand how much of the city is at desirable or critical levels for each indicator.

3.1. Importance Coefficients

The Importance Coefficient values of the ten indicators in this study are ranked and shown in order of highest to lowest importance in Figure 2. Indicators of travel, specifically inter-*barangay* trips (IC = 26.98), economy (IC = 25.48) and waste (IC = 8.26) rank above all other indicators for air, which is further ranked in order of $PM_{2.5}$ (IC = 7.40), NO_2 (IC = 6.92), CO (IC = 6.44), SO_2 (IC = 5.98), PM_{10} (IC = 4.64) and CO_2 (IC = 4.16). The intra-*barangay* trips show the lowest importance with IC = 3.73.

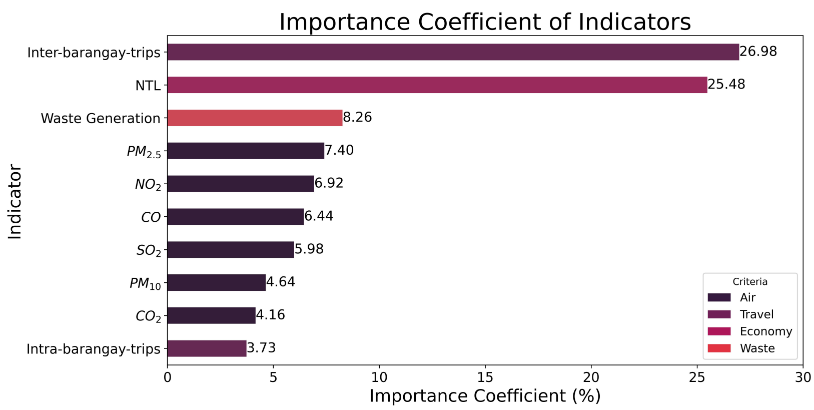

Figure 2. Importance Coefficient (IC) values of indicators used for assessing the UCCLN of Baguio City. The total IC for all air quality indicators has the greatest IC value, followed by the total IC values for travel indicators and NTL. Lastly, the IC value for waste generation is the smallest.

3.2. Distribution of DCC indicator levels

The data obtained for each indicator per temporal context and *barangay* were classified into DCC levels following Tables A1, A2 and A3. Histograms of the DCC indicator levels per temporal context are generated and distinguished by the granularity of the indicator, whether city-level or *barangay*-level.

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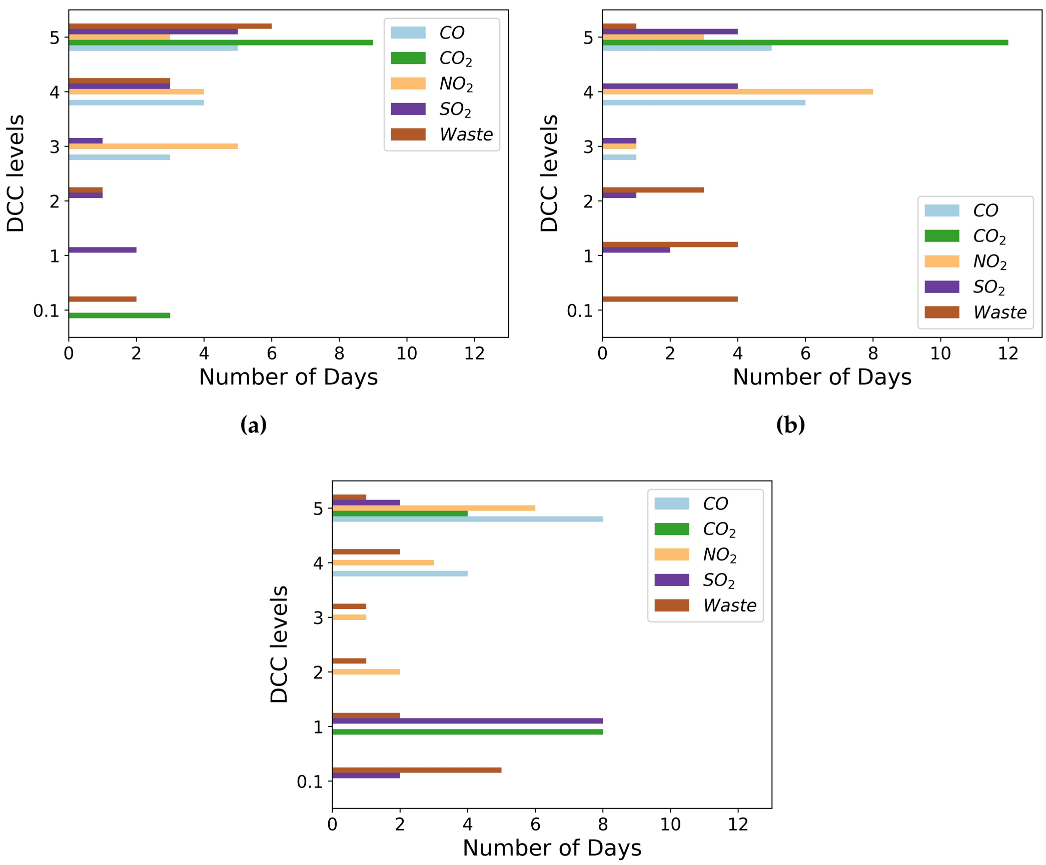
Based on the calculated DCCs of indicators for each temporal context (see Tables A1-A3), among the indicators that have no previously applied classifications, only three out of seven indicators (CO_2, SO_2, and NTL) have largely varying DCC levels with respect to the temporal context. Due to a lack of ground truth and modeling studies on the actual DCC levels of NTL and SO_2, the succeeding analyses and calculations of load numbers (LN) are based on the DCC levels per temporal context.

3.2.1. City-level DCC indicators

The city-level indicators in this study include Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen Dioxide (NO_2), Sulfur Dioxide (SO_2), and waste indicators. In Figure 3, CO and NO_2 appear consistently at high to critical levels of DCC for most days in all temporal contexts. These gases are commonly emitted by combustion of fuels such as diesel, kerosene, and charcoal used in cooking and transportation [38]. The SO_2 levels have a similar distribution on most regular days and holidays but drop on most days with events. Some man-made sources of SO_2 include the refinery and manufacturing industries [39], so locally mandated events can cause interruptions in their operation.

CO_2 is at the critical DCC level (level 5) for most days during holidays and even on regular days, albeit for slightly fewer days. On days with events, the number of days when CO_2 is at a critical level drops despite an expected influx of tourists. Regular activities and human mobility may be controlled during these times depending on the events organized by Baguio City. In contrast, waste generation levels range from medium to critical on most regular days while low on most holidays and days with events. A possible reason may be that waste collection during these times is interrupted.



(a) (b) (c)

Figure 3. DCC levels distribution of city-level indicators on (a) regular days, (b) holidays, and (c) days with events. Among the indicators, CO_2 is at the critical DCC level (level 5) for most days during holidays and even on regular days, albeit for slightly fewer days.

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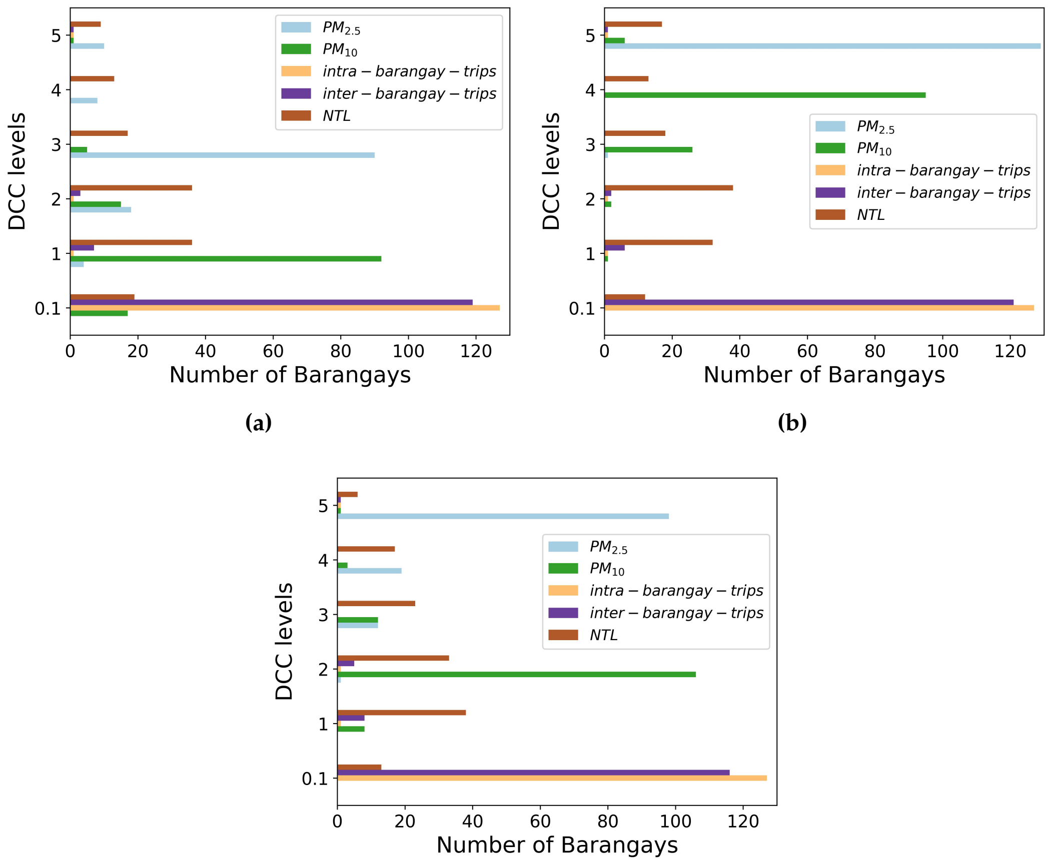
3.2.2. *Barangay*-level DCC indicators

The $PM_{2.5}$, PM_{10}, intra-*barangay* trips, inter-*barangay* trips, and NTL intensity indicator levels were averaged over all days of each temporal context to get their corresponding DCC levels for each *barangay*. In Figure 4, most *barangays* have high $PM_{2.5}$ DCC levels on regular days and very high to critical levels of $PM_{2.5}$ on holidays and days with events. Similarly, most of the *barangays* also show increasing PM_{10} DCC levels from regular days (desirable to low) to days with events (medium to high) to holidays (high to very high). Intra- and inter-*barangay* trips on most *barangays* are consistently at the desirable levels despite the consistently high to critical levels of DCC of CO and NO_2 on most days in Figure 3. Perhaps other sources of emission contribute to the soaring average concentration of CO and NO_2. NTL DCC levels, representative of economic activities in the city, range from desirable to critical in different *barangays*.



(a) (b) (c)

Figure 4. DCC levels distribution of *barangay*-level indicators on (a) regular days, (b) holidays, and (c) days with events. While most *barangays* have increased DCC levels for both $PM_{2.5}$ and PM_{10} from regular days to holidays and days with events, traffic are consistently at desirable levels.

3.3. Load Number

Load number (LN) represents the human-induced impacts or pressure due to the indicators. It incorporates the DCC levels and the ICs from expert opinions. The results of this section are presented for each context of temporal variation and organized as follows: (a) evaluation of the LNs of the city for each indicator criteria under different temporal contexts and (b) visualizations showing the maps of the total LN, LN per criteria (air quality, economic activity, traffic, waste generation), and (c) the maps of the difference in LN between the temporal variations.

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Based on the thresholds established from the results of the DCC calculations, the proportion of *barangays* with critical LN for each criterion is shown in Table 6. On regular days, only 3.85% *barangays* suffer from very high to critical levels of air pollution, while 12.31% and 99.23% *barangays* face the same levels on days with events and holidays, respectively. Regarding economic activities and urban vibrancy using NTL as a proxy, it is observed that on regular days, 14.61% of *barangays* have very high to critical levels while it improves to 10.0% and 9.23% of *barangays* on days with events and holidays, respectively, even accounting for the influx of visitors. The results of LN for traffic are consistent for all temporal contexts, indicating that only one *barangay* suffers from high to critical traffic levels. This result may indicate the need for more data, as only 500 GPS trackers were deployed. Additionally, the DCC levels based on the maximum values from these limited GPS data may need further verification on the ground. Finally, the city is at a very high to critical level of waste generation on regular days, on average. While this is computed, the ratio of total *barangays* classified under very high to critical levels of LN is not obtained due to the lack of spatial information.

Table 6. Ratio of *barangays* with critical LN. The air quality of almost the whole city is at critical state on holidays. However, the more *barangays* at desirable levels at the same time, balances it.

Criteria	Regular	Events	Holidays
Air	3.85%	12.31%	99.23%
Traffic	0.7%	0.7%	0.7%
Economy	14.61%	10.0%	9.23%
Waste	*no spatial information available*		

In general, the human-induced impacts in Baguio City shown in Figure 5a, as represented by the total load number, are greatest during holidays, followed by regular days and days with events. Looking at each criterion, the air quality in Figure 5b is worst during holidays, while the days of events have the best air quality, which could be attributed to the closure of main roads in the city's central area. In terms of NTL data as a proxy for economic activity in Figure 5d, the central area of the city consistently has the highest intensity during holidays, followed by days with events, with regular days having the least NTL intensity. Furthermore, it is observed that most *barangays* on the north and east sides of the city are consistently active during holidays and days with events. Regarding traffic in Figure 5c, the city's central area always generates the highest number of trips regardless of the temporal context. Interestingly, more places have worse traffic during days with events compared to regular days and holidays. These results are possibly because on holidays the influx of tourists into the city may be balanced by the outflux of residents. Meanwhile, during days of events, tourists enter the city, while residents are likely to go about their usual lives in the city. Finally, traffic is worse during regular days than during holidays, which could be supported by the idea that most residents stay in their homes during the holidays or have less movement compared to regular days. Regarding waste generation (Figure 5e), it is observed that the largest amount of waste is generated during regular days and holidays, while the least amount of waste is generated during days with events. This result is counterintuitive, and a more detailed inspection of the possible suspension of garbage collection during holidays should be investigated.

These results demonstrate the usefulness of monitoring and assessing the impacts of human-induced activities for different temporal contexts using EUCCLN. Provided that there is real-time data collection by sensors, the same approach can be used to nowcast human-induced impact, which will be a powerful tool for decision-makers and emergency response teams.

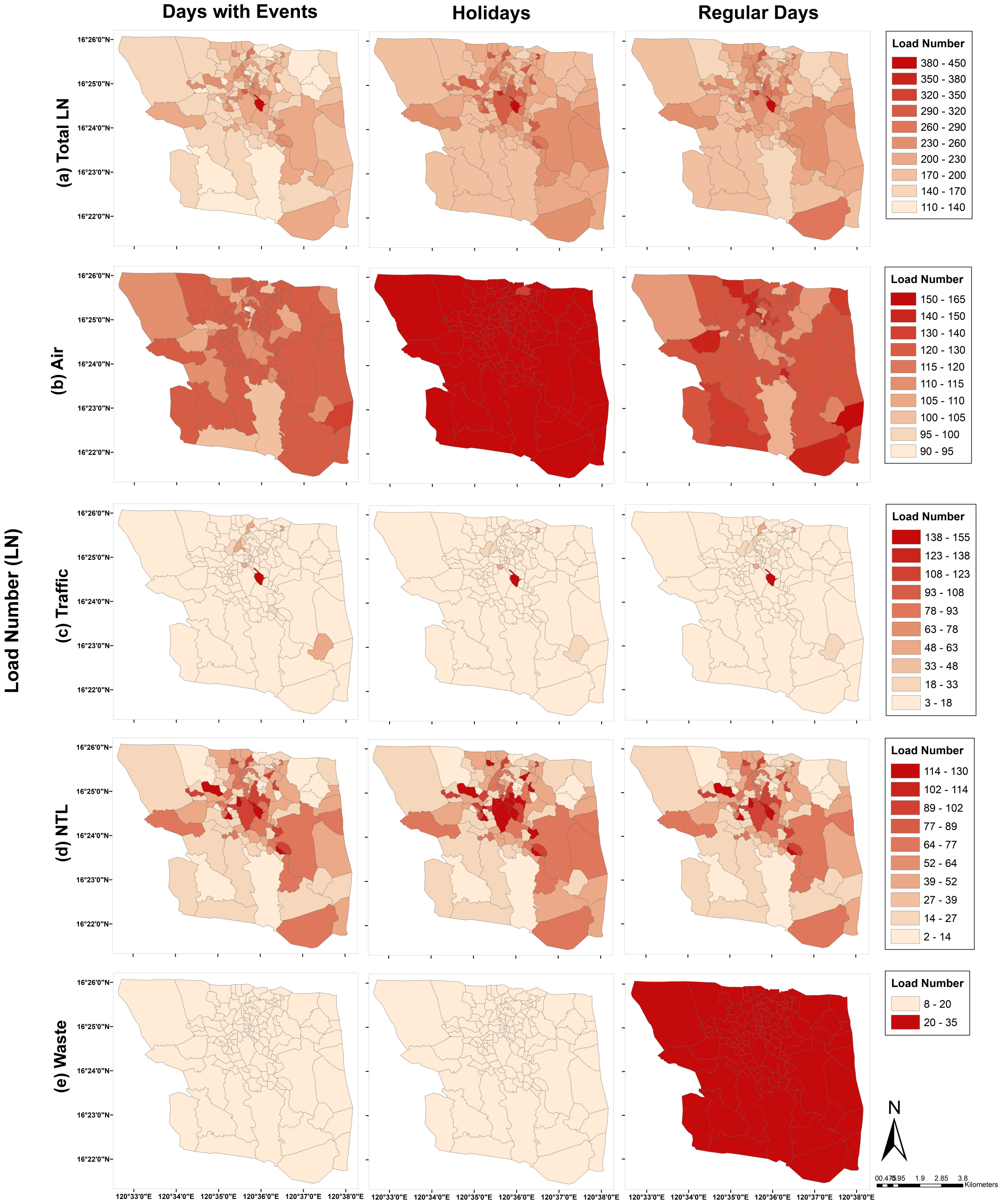

Figure 5. Visualization of LN levels for all *barangays* of Baguio City. (a) Total LN map and LN maps for the indicators: (b) air, (c) traffic, (d) NTL, and (e) waste; under different temporal contexts, *Days with Events*, *Holidays*, and *Regular Days*. Higher total LN numbers are found close to the central and eastern regions of the city. Notably, the LN for air is highest on holidays, indicating that the city experiences the worst pollution levels.

4. Discussion

Our results above show that EUCCLN used with GIS spatial visualization provides useful insights about the load number that a city experiences during different temporal contexts. Looking at the LN per indicator, the model results increase awareness regarding the areas that need more attention on days with events and during holidays. For a better understanding of the change in impact from regular days to days with events and holidays, differences in human-induced impacts between (a) regular

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and days with events, (b) regular and holidays, and (c) events and holidays are analyzed. Figure 6 shows the maps of the differences in LN of each criterion between temporal variations. Positive difference values in brown indicate that the first temporal context in the comparison has higher LN values than the second temporal context (e.g. *Regular Days - Holidays* in brown indicates that LN is higher on regular days than on holidays for the specific *barangay*). Green indicates otherwise. For instance, Figure 6a substantiates the interpretation that the LN for different *barangays* are highest for holidays, followed by regular days, and lowest for days with events.

In Figure 6b under *Regular Days-Holidays*, the results captured the severely increased levels of pollution in *barangay* Camp 7 (see Figure 1) during holidays compared to regular days. This area includes *Kennon road* which is infamous for being congested with vehicles during the holidays [40,41], as it serves as one of the gateways of Baguio. However, we do not see any similar result in terms of traffic in Figure 6c, since most GPS trackers are connected to taxis whose travel is mostly limited within the city. However, through these graphs showing the differences in total trips in each *barangay*, one can see which areas suffer the worst traffic during events (for example, the *barangays* in the vicinity of the Loakan Airport, where tourists also enter the city). More evidently, with the different plots, the central city area becomes less traffic during holidays than during days of events, as discussed in the previous section. This may be due to the idea that on holidays, tourists mainly move around the city, while residents prefer to rest. This coincides with the result of [42] in which resting activity was observed to increase during vacations, with a more pronounced magnitude if the duration of vacation is four days or more. The holidays included in Table 2 are more or less a week long. Although the results from the number of trips may not capture the comprehensive effect of events on holidays in most parts of the city, the use of NTL may be more informative in terms of measuring the change in load number of human-induced impacts on non-regular days from regular days (Figure 6d), as NTL has been demonstrated to capture information regarding economic activities and human movements [21]. Finally, the differences in waste generation in Figure 6e may provide insight into the improvements needed in the city. The high difference in waste generation between regular days and non-regular days may be indicative of the suspension of waste collection as workers may also be having their breaks on holidays or may not be able to collect waste on days with events because of a lack of access to collection sites as several roads are closed and blocked during events.

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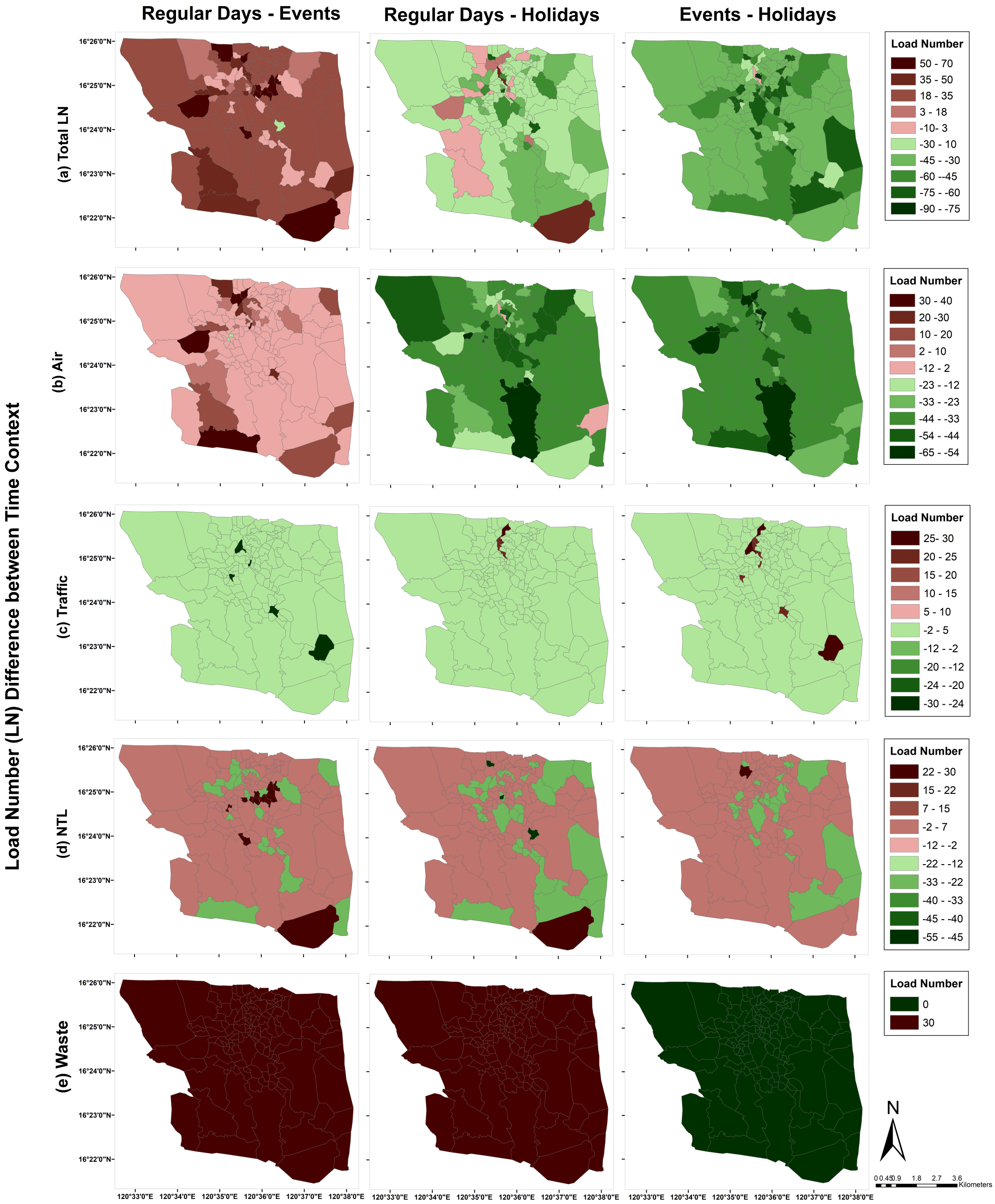

Figure 6. Visualization of the differences in LN levels for (a) Total LN, (b) air, (c) traffic, (d) NTL, and (e) waste, between different temporal contexts *Regular Days - Events*, *Regular Days -Holidays*, and *Events - Holidays*. A positive difference in brown indicates that the impact is greater in the first temporal context in the comparison, while a negative difference in green indicates otherwise. The differences highlight which *barangays* suffer from increased LN or worse impacts for each indicator and captured actual observations on the ground (e.g. the worsened pollution level at the main gateway of Baguio City (Camp 7 in Figure 1) on holidays.

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5. Conclusions

Globalization and rapid growth of cities require sustainable development of urban areas. Sustainability in this context is the examination of the various dynamic components called indicators that interact and impact the urban environment in the short and long term. This study focuses on Baguio City, the "Summer Capital of the Philippines," which attracts large crowds on holidays and whose local government actively promotes various events on non-holidays, thus having temporal context variations classified as regular days, days with events, and holidays. Here, changes in urban pressures for different temporal contexts based on spatial indicators grouped into air, traffic, economy, and waste were investigated using the enhanced urban carrying capacity load number (EUCCLN) model. The enhanced urban carrying capacity load number model has successfully assessed the pressures of human activities for different cities with its advantage of incorporating spatial information. In this work, the EUCCLN was used with three-step calculation of load number: (1) calculation of importance coefficients using AHP, (2) calculation of DCC levels, and (3) calculation of the load number (LN). An improvement to this model is incorporating a proxy economic indicator called the nighttime light (NTL). Our results showed that Baguio city experiences the worst pressures on air quality during holidays with 99.23% districts under very high to critical levels followed by regular and days with events. However, the total LN is balanced by favorable economic conditions with only 9.23% under very high to critical pressure levels. In this work, the capabilities of EUCCLN to effectively pinpoint areas experiencing critical states at any time have been demonstrated, advocating for targeted government monitoring. A possible powerful expansion of EUCCLN is nowcasting real-time data.

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Appendix A

Tables A1, A2, and A3 show the DCC classes of all indicators in different temporal contexts. In all tables, the $PM_{2.5}$ and PM_{10} indicators have the same ranges for all classes while the rest of the other indicators vary.

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Table A1. Indicators DCC on regular days

Regular Days							
		DCC					
Indices	Measuring Unit	0.1 (Desirable)	1 (Low)	2 (Medium)	3 (High)	4 (Threshold)	5 (Critical)
$PM_{2.5}$	$\mu g/m^3$	0-5	5.01-10	10.01-15	15.01-20	20.01-25	25<
PM_{10}	$\mu g/m^3$	0-15	15.01-20	20.01-30	30.01-40	40.01-50	50<
CO	$\mu mol/m^2$	0-0.129	0.130-0.258	0.259-0.387	0.388-0.516	0.517-0.645	0.646-0.774
CO_2	$\mu mol/m^2$	0-24.06	24.07-48.12	48.13-72.18	72.19-96.24	96.25-120.3	120.31-144.361
NO_2	$\mu mol/m^2$	0-0.008	0.009-0.016	0.017-0.024	0.025-0.032	0.033-0.04	0.041-0.046
SO_2	$\mu mol/m^2$	0-0.0035	0.0036-0.007	0.0071-0.0105	0.0106-0.014	0.0141-0.0175	0.0176-0.021
Intra-*barangay*	number of trips per 100 m^2	0-20.58	20.59-41.16	41.17-61.74	61.75-82.32	82.33-102.9	103.0-123.46
Inter-*barangay*	number of trips per 100 m^2	0-107.44	107.45-214.88	214.89-322.32	322.33-429.76	429.77-537.2	537.21-644.64
NTL (GDP)	W/m^2	0-86.11	86.12-172.22	172.23-258.33	258.34-344.44	344.45-430.55	430.55-516.67
Waste generation	kgs/ha	0-25	25.01-30.5	30.51-35.5	35.51-40.5	40.51-45.5	45.51-52.62

Table A2. Indicators DCC on holidays

Holidays							
		DCC					
Indices	Measuring Unit	0.1 (Desirable)	1 (Low)	2 (Medium)	3 (High)	4 (Threshold)	5 (Critical)
$PM_{2.5}$	$\mu g/m^3$	0-5	5.01-10	10.01-15	15.01-20	20.01-25	25<
PM_{10}	$\mu g/m^3$	0-15	15.01-20	20.01-30	30.01-40	40.01-50	50<
CO	$\mu mol/m^2$	0-0.133	0.134-0.266	0.267-0.399	0.4-0.532	0.533-0.665	0.666-0.795
CO_2	$\mu mol/m^2$	0-3.86	3.87-7.72	7.73-11.58	11.59-15.44	15.45-19.3	19.31-23.18
NO_2	$\mu mol/m^2$	0-0.008	0.009-0.016	0.017-0.024	0.025-0.032	0.033-0.04	0.049
SO_2	$\mu mol/m^2$	0-0.002	0.0021-0.004	0.0041-0.006	0.0061-0.008	0.0081-0.01	0.0101-0.013
Intra-*barangay*	number of trips per 100m^2	0-20.58	20.59-41.16	41.17-61.74	61.75-82.32	82.33-102.9	103.0-123.46
Inter-*barangay*	number of trips per 100m^2	0-105.00	105.01-210	210.01-315	315.01-420	420.01-525	525.01-630.03
NTL (GDP)	W/m^2	0-73.88	73.89-147.76	147.77-221.64	221.65-295.52	295.53-369.4	369.41-443.25
Waste generation	kgs/ha	0-25	25.01-35	35.01-40	40.01-50	50.01-60	60.01-78.51

Table A3. Indicators DCC on days with events

Days with Events							
		DCC					
Indices	Measuring Unit	0.1 (Desirable)	1 (Low)	2 (Medium)	3 (High)	4 (Threshold)	5 (Critical)
$PM_{2.5}$	$\mu g/m^3$	0-5	5.01-10	10.01-15	15.01-20	20.01-25	25<
PM_{10}	$\mu g/m^3$	0-15	15.01-20	20.01-30	30.01-40	40.01-50	50<
CO	$\mu mol/m^2$	0-0.12	0.121-0.24	0.241-36	0.361-0.48	0.481-0.60	0.601-0.717
CO_2	$\mu mol/m^2$	0-21.04	21.05-42.08	42.09-63.12	63.13-84.16	84.17-105.2	105.31-126.239
NO_2	$\mu mol/m^2$	0-0.007	0.008-0.014	0.015-0.021	0.022-0.028	0.029-0.035	0.036-0.0445
SO_2	$\mu mol/m^2$	0-0.008	0.009-0.016	0.017-0.024	0.025-0.032	0.033-0.04	0.041-0.049
Intra-*barangay*	number of trips per 100 m^2	0-20.58	20.59-41.16	41.17-61.74	61.75-82.32	82.33-102.9	103.0-123.46
Inter-*barangay*	number of trips per 100 m^2	0-83.32	83.33-166.64	166.65-249.96	249.97-333.28	333.29-416.6	416.61-499.92
NTL (GDP)	W/m^2	0-83.72	83.73-167.44	167.45-251.16	251.17-334.88	334.89-418.6	418.7-502.29
Waste generation	kgs/ha	0-25	25.01-30	30.01-35	35.01-40	40.01-45	45.01-50.23

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