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Forecast of Potential Areas of Urban Expansion in the Laguna de Bay Basin and Its Implications to Water Supply Security

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The Laguna de Bay Basin is a highly important economic and environmental resource with a variety of land and water uses. This study investigates the status and trends of the land cover change of the Laguna de Bay Basin, focusing on urban expansion. Using the Land Transformation Model (LTM), drivers of conversion of agricultural and natural land cover to built-up land were determined based on the land cover change between 2003 and 2015. Drivers identified include distance to rivers, distance to roads, distance to Laguna Lake, distance to existing built-up, slope, population density, soil type, temperature, and rainfall. A forecast of urban expansion assuming "business-as-usual" conditions to year 2050 shows the expansion of built-up areas southward of the National Capital Region towards the areas of Cavite, Batangas, and Laguna, and eastward to Rizal. This poses a risk to the water bodies near these areas. Potential implications on water quality and quantity, as components of overall water supply security, are discussed. A framework for future research integrating land use and land cover change (LULCC) and water supply security is proposed. The study recommends the continued implementation of integrated watershed management and the development of more trans-boundary management policies.

Keywords: Laguna de Bay Basin, land transformation model, land use and land cover (LULCC), urban expansion, water supply security

INTRODUCTION

LULCC can have profound effects on ecosystem functions in their watersheds or basins. Different types of land cover have varying needs and effects on its nearby water bodies such as agricultural land utilizing water more for irrigation and built-up areas for domestic purposes. In the Philippines, the Laguna de Bay Basin – spanning the provinces of Laguna, Rizal, and Metro Manila – provides food, water, and power supply to its inhabitants. With 58 sub-basins, 61 municipalities, and 12 cities, the basin is both a highly important economic and natural resource with many communities and industries depending on its land and water ecosystem services (Santos-Borja and Nepomuceno 2006). In recent years, it has been estimated that there are more than 14.6 million users of the Laguna de Bay region's resources (LLDA 2015b). Laguna Lake is the largest water body of the Laguna de Bay basin and contributes much to the ecosystem services that the basin provides. Historically, the lake's dominant use has been

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for fisheries but it has also been used for power supply, cooling of industrial equipment, transportation, and a floodwater receptacle (Santos-Borja and Nepomuceno 2006). Currently, it provides over 24,000 jobs for the fishing industry, supplies domestic water use through water providers, supports hydropower production, and is used as a waste sink for domestic, industrial, and toxic waste (WAVES 2016).

The 2003 land cover map of the Laguna de Bay basin indicates the large presence of agricultural fields and forest cover; however, after only seven years, built-up areas doubled in number while forest cover decreased with only one hectare of mangrove forest left in 2010 (WAVES 2016). Since 2010, a decrease in agricultural lands and an increase in built-up areas near the lakeshore have been observed in the Laguna de Bay Basin, which has been attributed to the rapid 'unplanned' urban sprawl characterized by the development or residential and commercial areas (WAVES 2016). These land cover change trends indicate an influx of people moving into the Laguna de Bay region, which means the already-large number of basin users is increasing. The conversion to built-up areas around Laguna de Bay Basin has implications on the use, quantity, and quality of Laguna Lake's waters. For example, waste production, dumping, and runoff coming from domestic and industrial sources contribute to nutrient loading in the lake and the degradation of its quality (Varca 2012). The varying and competing uses of land and water resources in the basin have caused also increased siltation, eutrophication, pollution, and loss of biodiversity (Nauta 2003), which is not only a problem for the environmental health of the basin but also for public health, and food and water security. Looking towards the future, unplanned or inappropriate LULCC may also aggravate climate change impacts in the area (Endo *et al.* 2017).

Thus, the varying demands for ecosystem services in the Laguna de Bay Basin combined with the increasing number of stakeholders make the management of urbanization in Laguna de Bay an important concern. The expansion of built-up areas is crucial input to an integrated approach to water resource management, which aims to coordinate land, water, and other related resources towards ecosystem viability and sustainability (Biswas 2008). Urban expansion can have a significant impact on the water resources of the basin, both in terms of water supply and water quality. Water supply pertains to the amount of available water resource, which may seem sufficient in the Laguna Lake; however, it is important to note that – in the context of human consumption – water quality plays a role that redefines supply as not just what is available but what is fit for the intended use. Given the potential impact of urban expansion on the ecosystem services of the Laguna de Bay Basin, it is important to understand the mechanisms behind it so that governing entities can anticipate trends and regulate the use of the lake. Some research has already been conducted in this field – Quintal and co-authors (2018) apply the LTM, a model that also combines the use of geographic information systems (GIS) with an artificial neural network (ANN), to investigate drivers of urban expansion specifically in the Seven Lakes area of San Pablo City, Laguna, from 1988 to 2003 and to 2015. Iizuka and co-authors (2017) investigated recent land use and land cover in the area around Laguna Lake from 2007 to 2015. Satellite imagery and spatial datasets of potential drivers of land cover change were analyzed via a multilayer perceptron neural network algorithm, and potential changes up to 2030 were forecasted using Markov Chain analysis. This study builds on and complements these previous analyses. The study aims to investigate the status and trends of conversion to built-up areas within the Laguna de Bay Basin, specifically in terms of the historical rate and drivers of conversion, and the potential areas of urban expansion in the future. The study applies the LTM to the region of the Laguna de Bay Basin, capturing potential drivers of land cover change at a scale larger than the previous studies. The scope encompasses the administrative boundaries of the Laguna Lake Development Authority (LLDA), the government agency under the Department of Environment and Natural Resources, which is tasked to promote the balanced development of the Laguna Lake area. LLDA has ongoing initiatives that implement an integrated water resource management in relation to the comprehensive land use plans (CLUPs) of local governments. The focus on urban expansion is intended to aid in identifying the important drivers of change that can be addressed through the management of land resources. Areas of potential urban expansion in the future are projected based on validated drivers. Potential implications on ecosystem services – particularly in terms of water supply and quality of the lake – as relevant to the question of water supply security, are discussed.

MATERIALS AND METHODS

The LTM

LTM is employed in this study. The LTM is a forecasting model that conducts spatial analysis to determine the influence of drivers to changes in land cover. It is a combination of a GIS and an ANN (Pijanowski *et al.* 2002a). A GIS is used for spatial analysis given a set of drivers; meanwhile, an ANN is used to identify the existing trends of an area given its history and is used to represent complex behavior in numerical form (Pijanowski *et al.* 2002a). It is flexible and can be adapted for the type of land cover change to be investigated. For example, it has – on the one hand – been used to forecast urbanization (Quintal *et al.* 2018, Pijanowski *et al.* 2002b), but it has also been used to forecast the appearance of vacant land (Newman *et al.* 2016). LTM is best used in studies that cover large-scale trends (Pijanowski *et al.* 2000).

Validating Drivers of Conversion to Built-up Land

The LTM is calibrated by identifying a set of drivers of the land cover change to be forecasted, simulating the change for a historical period, and comparing the output to the known historical change. This study simulates conversion to built-up land in the Laguna de Bay Basin between 2003 and 2015 (additional analyses for the periods 2003–2010 and 2010–2015 can be found in Appendix I). Four categories of land cover were used in the preparation of 2003 and 2015 maps: Built-up, Agricultural, Water, and Natural (Figures 1 and 2). The reference 2015 land cover map is compared against the 2015 map forecasted by the LTM to validate the drivers selected.

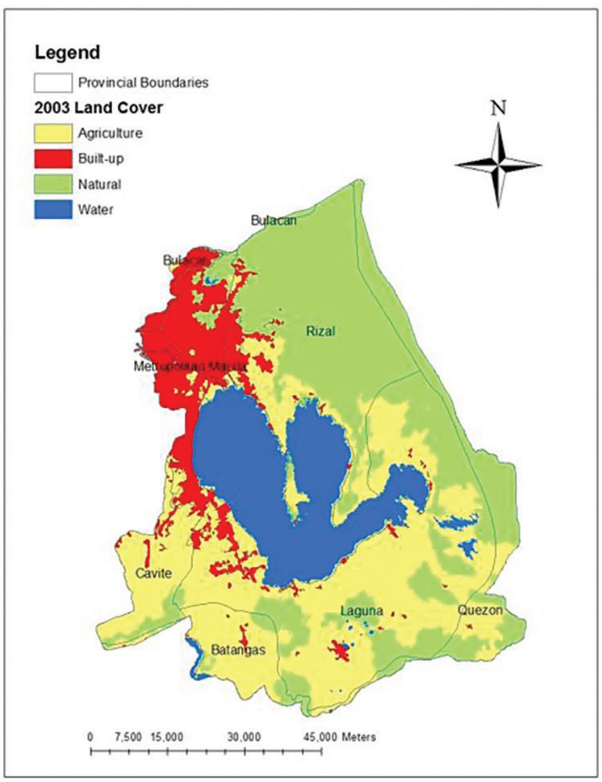

Figure 1. 2003 harmonized land cover map [raw (unprocessed) land cover map obtained from NAMRIA; boundaries map from LLDA].

Drivers of conversion to built-up land can be geographical constraints, policies, or demand for land (Pijanowski *et al.* 2009). Geographical constraints would pertain to biophysical factors such as topography as it was determined to have a strong influence on conversion to built-up (Lambin *et al.* 2001). An increase in one unit of the slope was observed to decrease the probability of an area to be converted into built-up by 1.7% (Huang *et al.* 2015). The type of soil in an area poses serious limitations on the type of land use that can be built with cracked foundations and walls on infrastructure to have been caused by unstable soils (Laker 2007). Climate factors may also influence usability or preferred uses of the land *e.g.*, for agriculture (Iizuka *et al.* 2017).

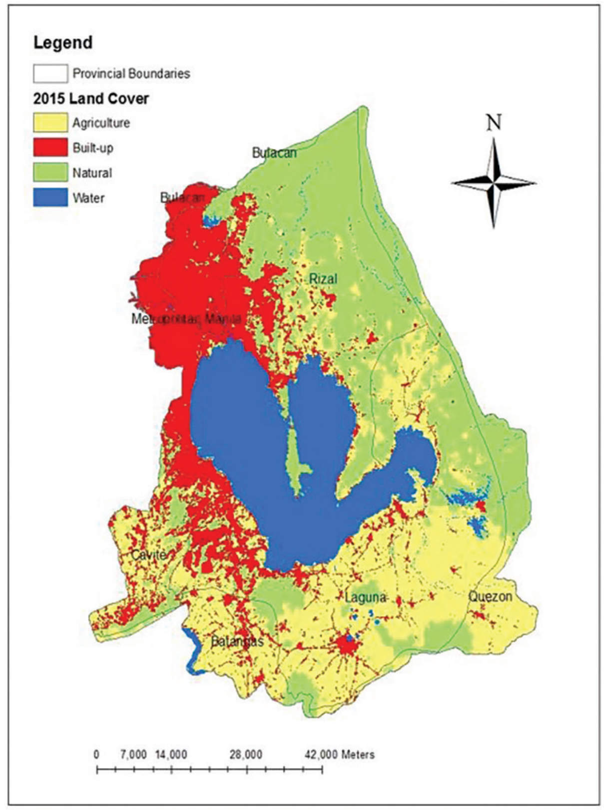

Figure 2. 2015 harmonized land cover map [raw (unprocessed) land cover map obtained from NAMRIA; boundaries map from LLDA].

The demand for land would pertain to population density as it has been identified to be a major driver for the conversion to built-up. With demographic development comes the need for more land to address the residential and commercial needs of the people (Zondag and Borsboom 2009). The conversion to built-up land tends to be near existing built-up areas due to lower development expenses, and near road networks due to ease of access (Huang *et al.* 2015). People tend to build settlements near lakes and rivers as these are a rich natural resource that provides livelihood. Quintal and co-authors (2018) identified distance to roads, distance to existing built-up areas, distances to lakes, population density, distance to trails, and slope to be driving forces for the conversion to built-up areas in San Pablo City, Philippines. Iizuka and co-authors (2017) found that datasets on population density and night lights (which could be an indicator of existing built-up areas) were found to correlate well to conversions to built-up areas.

Given this literature, the following drivers for urban expansion were tested for the Laguna de Bay Basin: (1) distance to roads, (2) distance to existing built-up areas, (3) distance to Laguna Lake, (4) distance to rivers, (5) population density, (6) slope, (7) soil type, (8) temperature, and (9) rainfall. The influence of water resources on urban expansion is considered through the inclusion of proximity to the lakes and its rivers/tributaries as a driver. Datasets used were those that are freely and/or publicly available. A summary of the datasets used can be found in Table 1. Unfortunately, the temporal coverage of the available datasets/maps of the potential drivers does not all match the available maps for land cover. The slope map of 2010 would still be a reliable estimate given that no major geologic movements have happened in the area. In the case of the 2017 road map, while major thoroughfares already existed in 2003–2015, there are likely minor roads in the map not yet constructed during the time of the study. The maps representing "present-day" climate available through World Clim (Hijmans *et al.* 2015) are that of a 1960–1990 baseline. While temperatures have been found to be increasing since then (0.0108 °C/yr over the country, from 1951–2010), no significant trend in rainfall has been detected in the area (PAGASA 2011). The impact of the uncertainties introduced by these depends on the relative weights of these drivers as determined during the validation step using the LTM.

Validation of drivers for urban expansion involved preparing maps of these factors for input to LTM using GIS methods, then training and testing the neural network to determine the best combination of drivers that would give the highest accuracy of simulated land cover change compared to actual land cover change. The ArcGIS platform was used for input preparation for LTM. The Euclidean distance tool of Spatial Analyst in ArcMap was used to create a gradient map for the distance to roads, distance to rivers, distance to Laguna Lake, and distance to existing built-up areas maps. For the population density, rainfall, and temperature maps, the scope, cell size, and projection, were adjusted for each pixel already contained a value. Using the Aggregate and Resample tool, the cell size and number of columns and rows of all maps were adjusted to 100 by 100 m, and 838 and 1047, respectively. For the rest of the drivers, slope and soil type, number codes were assigned to each category by manipulation of the attribute table. This allowed LTM to process each cell. All of the maps were converted into ASCII format for LTM to process (all the driver maps can be found in Appendix II).

Using LTM, the neural network was trained with the 2003–2015 dataset. The 2015 predicted change map produced by LTM was compared with the 2015 existing built-up areas map, processed from land cover maps from the National Mapping and Resource Information Authority (NAMRIA). LTM generates two metrics: a PCM value and a Kappa value (Table 2). The PCM compares the accuracy of the predicted change to the real change map by comparing the number of cells that transformed between the forecast model and the actual map. If the PCM obtained is greater than or equal to 80%, this denotes an exceptionally accurate forecast map (HEMA 2006). The Kappa value calculates the model's percent success relative to the percent chance. If the Kappa value is between 0.4 and 0.6, this indicates a relatively good forecast map (Pontius 2002; Sousa *et al.* 2002, as cited in Pijanowski *et al.* 2005). To determine the Kappa value, the LTM tracks cells that are "*True Positives*," the ones that were predicted to transition and did undergo real change. Cells labeled "*False Positive*" are the ones that were predicted to transition but did not undergo real change. Cells labeled "*True Negative*" are the ones that

Table 1. Summary of key spatial data for LTM.

Inputs	Data source	Format	Spatial coverage	Temporal coverage	Data role
Rainfall	World Clim (Hijmans *et al.* 2015)	ESRI	Global	1960–1990	Driver input
Temperature	World Clim (Hijmans *et al.* 2015)	ESRI	Global	1960–1990	Driver input
Slope	NAMRIA	Shapefile (.shp)	Laguna de Bay Basin	2010	Driver input
Roads	NAMRIA and Open Street Map	Shapefile (.shp)	Laguna de Bay Basin	2017	Driver input
Rivers	LLDA	Shapefile (.shp)	Laguna de Bay Basin	2015	Driver input
Laguna Lake	NAMRIA	Shapefile (.shp)	Laguna de Bay Basin	2003	Driver input
Soil type	NAMRIA	Shapefile (.shp)	Philippines	2013	Driver input
Population density	SEDAC	ASCII (.asc)	Laguna de Bay Basin	2000, 2005, 2010, and 2015	Driver input
Historical land cover maps	NAMRIA	Shapefile (.shp)	Laguna de Bay Basin	2003, 2010, and 2015	Base map
Provincial boundaries	LLDA	Shapefile (.shp)	Philippines	2000	Base map

Table 2. Range and its corresponding indicator for PCM and Kappa values.

Range of PCM	Indicator	Range of Kappa	Indicator
< 40%	Unacceptable	0.0–0.2	Very poor
40–60%	Acceptable	0.2–0.4	Poor
60–80%	Good	0.4–0.6	Acceptable
> 80%	Exceptional	0.6–0.8	Great

Source: Sousa *et al.* (2002, as cited in Pijanowski *et al.* 2005) and HEMA (2006)

were predicted not to transition and did not undergo real change. Cells labeled "*False Negative*" are the ones that were predicted not to transition but did undergo real change.

To validate the drivers, ten (10) simulations were conducted – a simulation with all nine drivers were used, and the rest of the simulations each having one driver removed. The relative weight of each driver was also assessed by comparing the PCM and Kappa metrics of the simulation excluding the driver with the simulation including all drivers. For example, the relative weight that indicates the importance of a single driver was derived by getting the difference in, say, the PCM of the simulation of all drivers and the simulation without the single driver, then expressing that value as a percentage of the PCM with all drivers. The set of drivers for the simulation with the highest PCM and Kappa metrics was selected to forecast conversion to built-up land in 2050.

Forecasting Potential Areas for Urban Expansion

The trained neural network using the optimal set of drivers from the 2003–2015 runs was used to generate a forecast map of potential areas of urban expansion in the future. Based on the relative weights and the distribution of the drivers, the LTM selects the grid cells that are most likely to transition into a built area. However, a key limitation of the LTM is that while it can identify areas of probable change, it cannot predict when this change will occur and simulating different rates of change is not within current model capabilities. In this study, we present a conservative forecast for 2050 assuming a "business-as-usual" scenario, which applied the same rate of change for the conversion to built-up areas, using the average number of cells per year that transitioned between 2003 and 2015. The 2015 existing built-up areas map from NAMRIA served as the base map. Potential implications for water supply security are discussed.

RESULTS

A total of 53,798 built-up cells of size 100 m by 100 m were identified to have transitioned, equivalent to roughly 4,483.167 cells per year, from 2003–2015. In a span of 12 years, an 81.65% increase in built-up land was experienced in the basin, at the expense of built-up and natural areas. An increase of 17.32% in agricultural land was actually observed during the last five years, from 2010 to 2015, but there was an overall decrease in agriculture and natural land since 2003. Roughly 575 sq. km of built-up land existed in 2003, increasing to 1040 sq. km in 2015.

Based on the validation of drivers, the distance to roads driver was determined to be the most significant contributor to this increase in built-up land, with a weight of 10.57% (Table 3). The second most significant driver is the distance to existing built-up areas with a weighted percent of 1.82. These are consistent with the results from the study of Quintal and co-authors (2018), which focused on San Pablo City, Laguna. The distance to Laguna Lake driver and the distance to rivers driver come in third and fifth respectively as the most significant. Climate factors such as temperature and rainfall are of lower influence, raking fourth and fifth, respectively. This may be because the variations in these factors within the study area are relatively small.

Iizuka and co-authors (2017) had also found that distances to secondary roads and canals were of "good" explanatory power for modeling built-up areas. Overall, these results suggest that access to services becomes a stronger factor for conversion to built-up than direct proximity to the water

Table 3. Weights per driver from 2003 to 2015 run.

Drivers removed	PCM (%)	Weight of driver removed (%)	Kappa	Difference
All nine drivers present	64.864530	N/A	0.552891	N/A
Distance to roads	58.010491	10.57	0.477567	0.075324
Distance to existing built-up areas	63.683298	1.82	0.539917	0.012974
Distance to Laguna Lake	64.005452	1.32	0.543450	0.009441
Temperature	64.117259	1.15	0.545523	0.007368
Distance to rivers	64.263588	0.93	0.546287	0.006604
Rainfall	64.344474	0.80	0.547932	0.004959
Population density	64.355479	0.78	0.549214	0.003677
Soil type	64.565160	0.46	0.553516	–0.000625
Slope	64.848009	0.03	0.552710	0.000181

bodies after the initial settlements and road networks have been established. However, Iizuka and co-authors (2017) had found population density to have high influence on built-up areas; in this study, it is ranked in the bottom three of the 10 drivers investigated. The difference in the scope of the study areas may account for this, and further studies can be conducted to ascertain the weight of population density as a factor driving LULCC at different scales.

Considering both the PCM and Kappa metrics (Table 3), the simulation with all nine drivers was considered as having the best results. The PCM and Kappa values are 64.86% and 0.55 respectively, which fall under the "good" and "acceptable" ranges of values, respectively. Figure 3 compares the 2015 forecast against the actual land cover using the simulation with all nine drivers. Most of the cells correctly predicted to transition to urban (True Positives) are found in close proximity with existing built-up areas in 2003. These are in the eastern portion of Laguna and parts of Cavite, Batangas, and Rizal. There are cells that were not predicted to change but did (False Negatives), mostly along the southern portion of the basin, along road networks farther from existing built-up land.

All nine drivers were therefore used to forecast conversion to built-up land from 2015 to 2050, assuming the "business-as-usual" rate of 4,483.167 cells per year (Figure 4). However, given that the LTM does not simulate rates of conversion, this urban expansion may occur earlier with faster rates of conversion (*i.e.*, by 2035 at double the rate of land cover change, or even earlier with exponential growth). The results show that most of the increase in built-up areas will occur in the southern part of the bay. Built-up areas appear southward of the National Capital Region moving down towards the areas of Cavite and Batangas. Laguna province is expected to experience the greatest increase in built-up land cover. North of the bay, the southwestern portion of the Rizal province is also predicted to transition to built-up. Currently, these areas are primarily agricultural. The change is likely to be a result of the rapid urbanization in those areas since the Philippine Statistics Authority reported that Rizal province had the highest rate of urbanization (92.7%) among the provinces in the country; this was followed by Laguna province at 72% (PSA 2013).

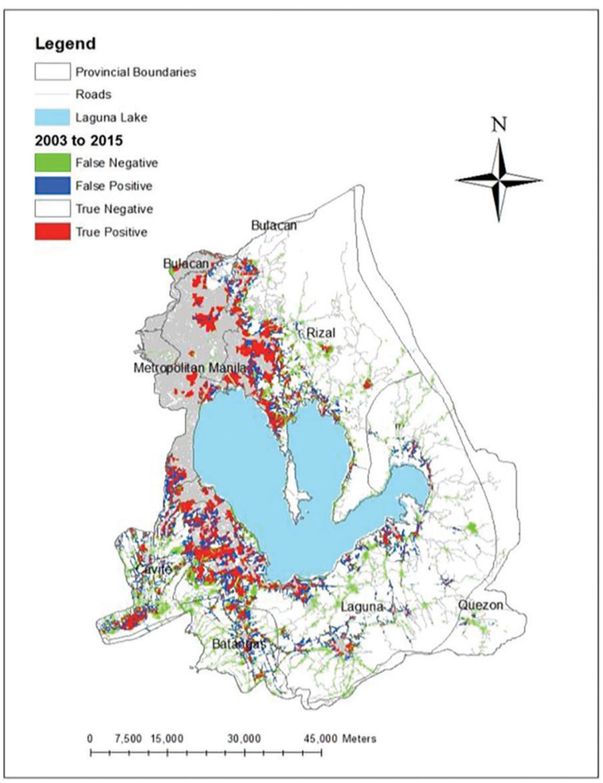

Figure 3. Forecast skill of LTM between for increase in built-up areas between 2003 and 2015 (Laguna Lake map from NAMRIA; boundaries map from the LLDA).

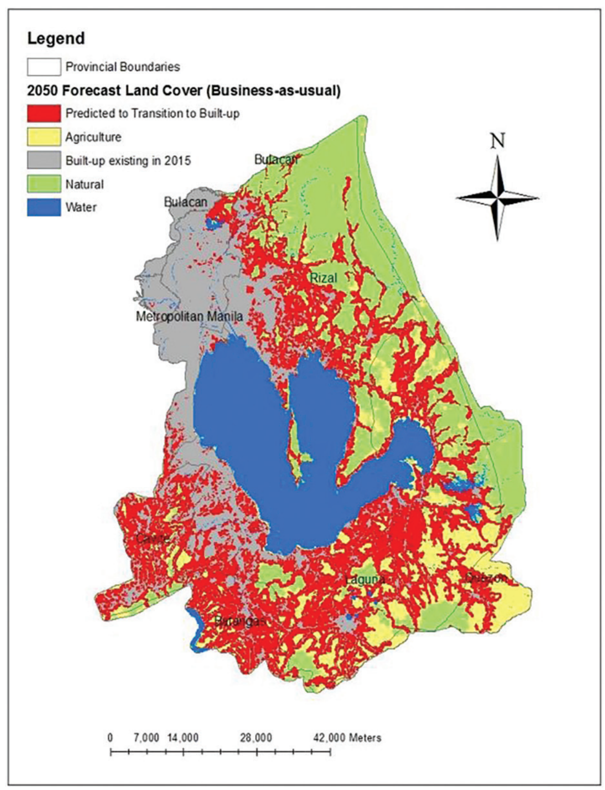

Figure 4. 2050 forecast for conversion to built-up land assuming "business-as-usual" conditions.

DISCUSSION

The results of the historical land cover change analysis are in agreement with existing literature, which documents that forest cover and agricultural land decreased to make way for the development of residential and commercial areas (WAVES 2016). The distance to road networks ranked highest among the tested drivers of conversion to built-up areas, with the proximity to existing built-up areas and to the lake came in a close second and third in the ranking. This implies that accessibility is still more a primary or explicit consideration compared to the value presented by proximity to the lake and the ecosystem services this may provide.

The southern portion of the basin is projected to experience a large increase in built-up areas in the near future. This is of concern to both the water supply and water quality of Laguna Lake. With the forecasted increase in built-up areas will come the need to provide more water for the associated domestic and commercial developments. The 2015 Annual Report of LLDA stated that the basin cumulatively received 90,151.34 mm of rainfall for the year 2012. The highest surface water generation came from the Marikina sub-basin, which generated 20% of the total, followed by the Pagsanjan sub-basin with 12%; the remaining sub-basins comprised the remaining 68% of total surface water generation (LLDA 2015a). However, an ecosystem account developed for the Laguna de Bay reported an average total extractive lake usage of 204,984 million liters per year based on LLDA surface water permits from 2000 to 2012 (WAVES 2016). The water balance account model of the Wealth Accounting and the Valuation of Ecosystem Services (2016) shows negative values for change in lake storage (*i.e.*, depletion) for 10 years of the 13-year simulation period (2000–2012). Ascertaining the viability of this surface water supply is of concern, given that a water resources assessment released by the National Water Resources Board (NWRB 2004), which included areas in and around Metro Manila, found that the groundwater supply is not sustainable due to heavy abstraction and saltwater intrusion, and recommended diverting to surface water as an alternative supply source. Looking towards the future, the CALABARZON region (Cavite, Laguna, Batangas, Rizal, Quezon) is projected to have relatively high population growth rate (1.31% between 2010 and 2045) and will remain as the region with the highest number of people (20.1 million by 2045) (PSA 2015). The long-term water supply of Laguna de Bay is further threatened due to the region's susceptibility to extreme weather events. Precipitation forecasts under an RCP6.0 scenario showed a marked decrease in rainfall in the province of Luzon for years 2031–2060 (Gotangco *et al.* 2017). Representative Concentration Pathways (RCPs) are scenarios that depict 2100 with varying levels of radiative forcing, with RCP5.0 being a medium scenario of 6 W/m^2 (van Vuuren *et al.* 2011). Climate projections for the Philippines (Cinco *et al.* 2013) show that wet seasons becoming wetter but dry seasons becoming drier.

Compounding the potential problems in the water supply is that the water quality may not be fit for needed uses. Mapping existing data on water quality parameters of the lake shows that the sections with the worst water quality, based on a scorecard released by LLDA (2013), are those proximate to predominantly built-up areas (Figure 5) (details on water quality can be found in Appendix III). While the water quality parameters of the lake currently meet the minimum legal requirements for fishery waters, the increasing built-up land threatens to change this if no substantial treatment and management interventions are put in place. At present, we already know that most of the pollution discharge comes from improper waste management practices (*e.g.*, no sewage systems in place) in the communities around the basin – with 81% of BOD load domestically-sourced, 9% from industry, 5% from agriculture, 2% from forests, and 3% from solid wastes (WAVES 2016). The built-up area increase in South Bay also poses a threat to the sanctuary located in the area.

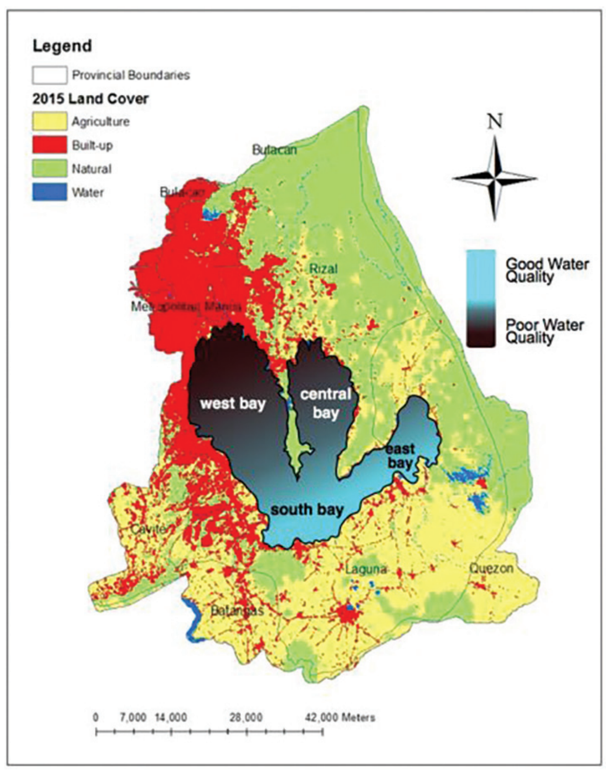

Figure 5. 2015 land cover map of Laguna de Bay Basin with Laguna Lake water quality scores [boundaries map from LLDA; raw (unprocessed) land cover map obtained from NAMRIA; water quality from the LLDA LDB ecosystem report card (2013) based on compliance with water quality standards for Class C waters under DAO 08, 2016].

The declining water quality also threatens to affect the basin's ability to be a domestic water resource. Thus, an integrated water resource management approach that harmonizes with comprehensive LULCC planning needs to be implemented in the context of holistic water supply security (Bigas 2013). This takes into account both the direct supply risk when the volume of water available cannot meet the demand and the indirect supply risk when the water that is available is of unsuitable quality for its intended use. Figure 6 summarizes literature and findings presented into a proposed framework for research integrating LULCC and water supply security. Land cover and land use influence the quantity and quality of the existing water supply. For urban areas, water resources function as both sources of ecosystem services and sinks for effluents of a growing population. In this same way, both water quantity and quality affect the type of land conversion that may occur, since the use of the land is also dependent on the availability of water supply. In the case of urban expansion, given the research already available on trends and drivers of urban expansion, more research is required to extend this to a more comprehensive impact assessment of built-up areas on water supply security, given different scenarios for water supply (*e.g.*, surface water *vs.* groundwater) and for wastewater treatment and management.

CONCLUSION

The analysis of urban expansion showed that built-up land in the Laguna de Bay basin has almost doubled between 2003 and 2015, with 575 sq. km of built-up land increasing to 1040 sq. km. Urban areas were initially concentrated in the Metropolitan Manila area, but forecasts show Cavite, Batangas, Laguna, and Rizal are expected to experience the greatest increase in urban expansion. Distance to roads was identified to be the most significant driver towards the conversion to built-up. This suggests that accessibility is a major contributing factor to urban expansion in this area, compared to proximity to the lake, which ranks third among the drivers. Distance to existing built-up areas ranked second, which is indicative of urban sprawl.

Given the drivers of urban expansion, the LTM forecasts that the southern portion of the bay will likely experience a drastic increase in built-up areas. This, along with projections for population growth, poses concerns to the sustainability of Laguna de Bay's ecosystem services and to the water supply security of the basin. Existing studies already show the negative account of water supply and declining water quality (including that of groundwater sources); thus, if current trends in the conversion to built-up land remain "business-as-usual," the available water supply may not be sufficient or of adequate quality for its increasing demand and various uses. Thus, more research is needed into the impacts of urban expansion in the Laguna de Bay Basin, in the context of holistic water supply security and an integrated approach to water resources management.

LLDA has already begun to implement an integrated water resource management program in the Silang – Sta. Rosa sub-basin, which is a step in the right direction. Currently, CLUPs are developed at the city/municipal level and the analyses largely focus on impacts within city boundaries. Since environmental processes affecting land and water resources are trans-boundary, an integrative approach to basin management – which reconciles the CLUP per sub-basin – would be crucial.

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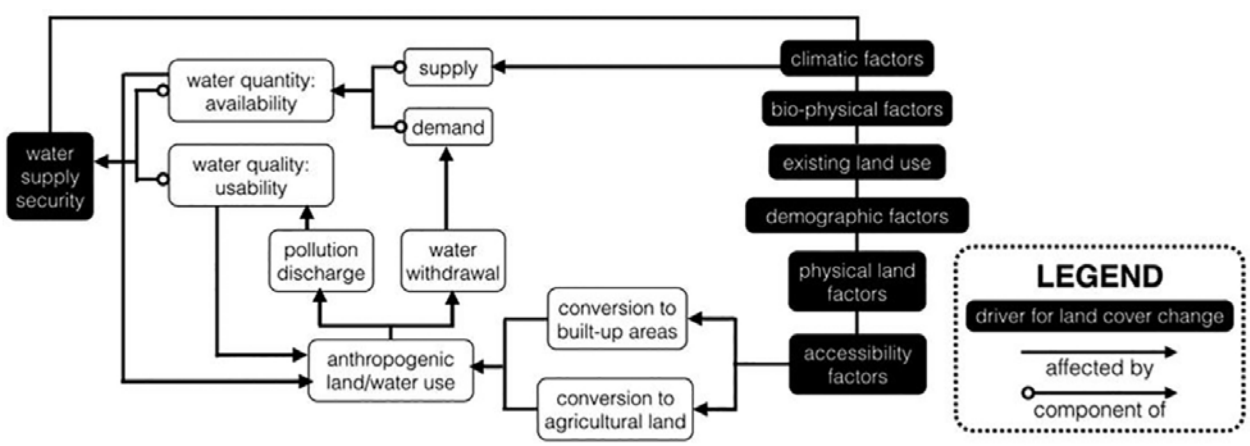

Figure 6. A proposed framework for integrative LULCC and water supply security research.

NOTES ON APPENDICES:

The complete appendices section of the study is accessible at https://drive.google.com/file/d/1G_0se_tn2EpMIql4-WLqb1kUOCrNVEB-/view?usp=sharing

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APPENDIX I

Additional Simulations: 2003–2010 and 2010–2015

Set 1: 2003–2010

The neural network was trained using the 2003 map as the initial land cover and 2010 map as the final land cover. With a seven-year gap for the 2003–2010 run, a total of 47,316 cells transitioned to built-up or approximately 6,759.43 cells per year. The run that yielded the highest PCM and Kappa values (62.312034% and 0.538443, respectively) was that of using all nine drivers (refer to Table A.1 below). PCM values above 60% are deemed good (Purdue University 2006). Meanwhile, a Kappa value between 0.4 and 0.6 indicates an acceptable forecast map (Pontius 2001; Sousa *et al.* 2002, as cited in Pijanowski *et al.* 2005).

The correctly predicted cells to transition are found close in proximity with existing built-up areas from the 2003 base map. This can be seen more evidently in the weighted difference of the distance to existing built-up areas PCM value to all drivers present run, the highest compared to the rest of the drivers at 35.04%. Cells, therefore, closest to existing built-up areas were identified by LTM to transition. However, the results of the real change map show otherwise. Majority of the cells that underwent real change but were not predicted to change or "*False Negatives*" branch out away from existing built-up areas into agricultural land. These cells also follow the delineation of the roads map. LTM ranked distance to roads as second in strength of influence but provided it with much less weight than the distance to existing built-up areas driver.

Set 2: 2010–2015

A total of 16,967 cells transitioned to built-up within the five-year gap of the second time frame with an average of 3,393.4 cells per year. Table A.2 summarizes the PCM and Kappa metrics, which reveal that the model is not acceptable to use for forecasting beyond 2015. This is likely because there were not enough cells that transitioned to built-up to adequately train the LTM.

Table A.1. Weights per driver from 2003 to 2010 run.

Drivers removed	PCM (%)	Weight of driver removed (%)	Kappa	Difference
All nine drivers present	62.312034	N/A	0.538443	N/A
Distance to rivers	61.934947	0.61	0.53434	0.00410
Distance to roads	54.874381	11.94	0.457514	0.08093
Distance to Laguna Lake	61.215477	1.76	0.526511	0.01193
Distance to existing built-up areas	40.477953	35.04	0.300873	0.23757
Slope	61.356591	1.53	0.528047	0.01040
Population density	61.065819	2.00	0.526729	0.01171
Soil type	62.032147	0.45	0.539361	–0.00092
Temperature	61.560120	1.21	0.531286	0.00716
Rainfall	61.337491	1.56	0.528497	0.00995

Table A.2. Weights per driver from 2010 to 2015 run.

Drivers removed	PCM (%)	Weight of driver removed (%)	Kappa	Difference
All 9 drivers present	39.295783	N/A	0.348155	N/A
Distance to rivers	37.027755	5.77	0.325003	0.02315
Distance to roads	34.615626	11.91	0.300379	0.04778
Distance to Laguna Lake	37.704404	4.05	0.331910	0.01625
Distance to existing built-up areas	35.104317	10.67	0.305380	0.04278
Slope	38.044633	3.18	0.335797	0.01236
Population density	36.945782	5.98	0.324627	0.02353
Soil type	36.725416	6.54	0.323096	0.02506
Temperature	38.407245	2.26	0.339798	0.00836
Rainfall	35.925000	8.58	0.314314	0.03384

APPENDIX II

Additional Maps

Driver maps are shown in Figures A.1 to A.4.

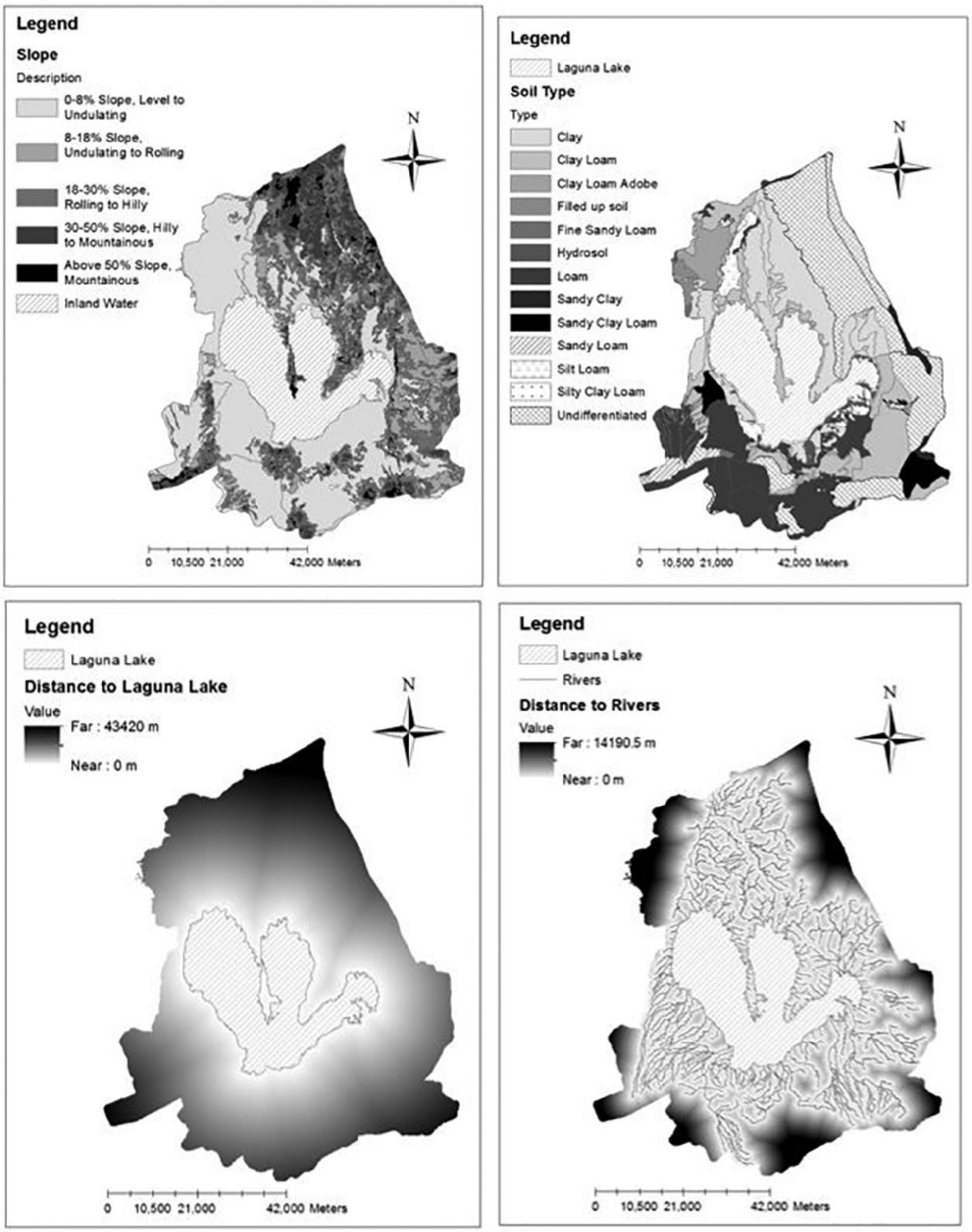

Figure A.1. From left to right, top row: (A) slope and (B) soil type; from left to right, bottom row: (C) distance to Laguna Lake; and (D) distance to rivers (original base maps obtained from NAMRIA).

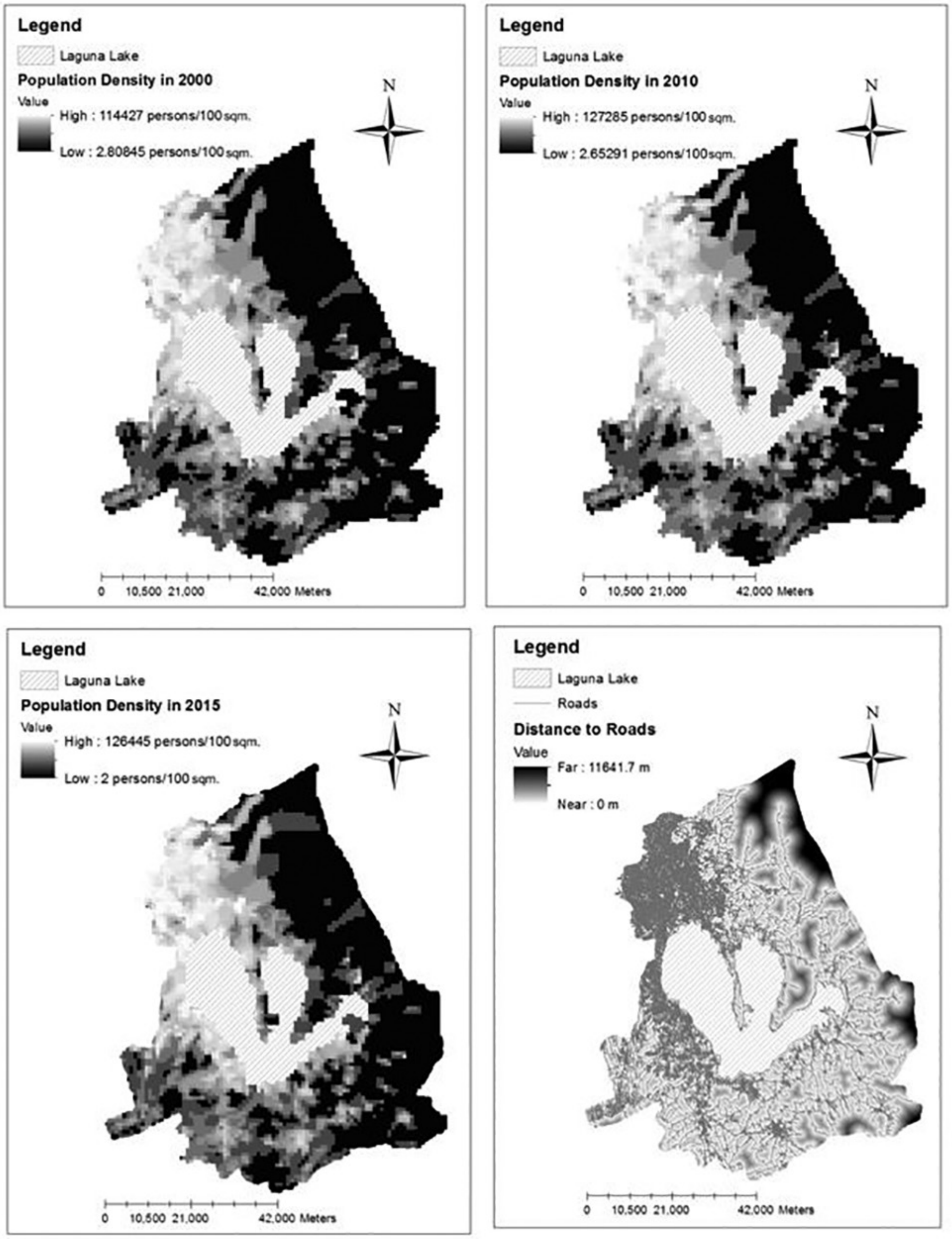

Figure A.2. From left to right, top row: (A) 2000 population density and (B) 2010 population density; from left to right, bottom row: (C) 2015 population density; and (D) distance to roads (population density maps obtained from Socioeconomic Data and Applications Center; raw roads map obtained from Open Street Map).

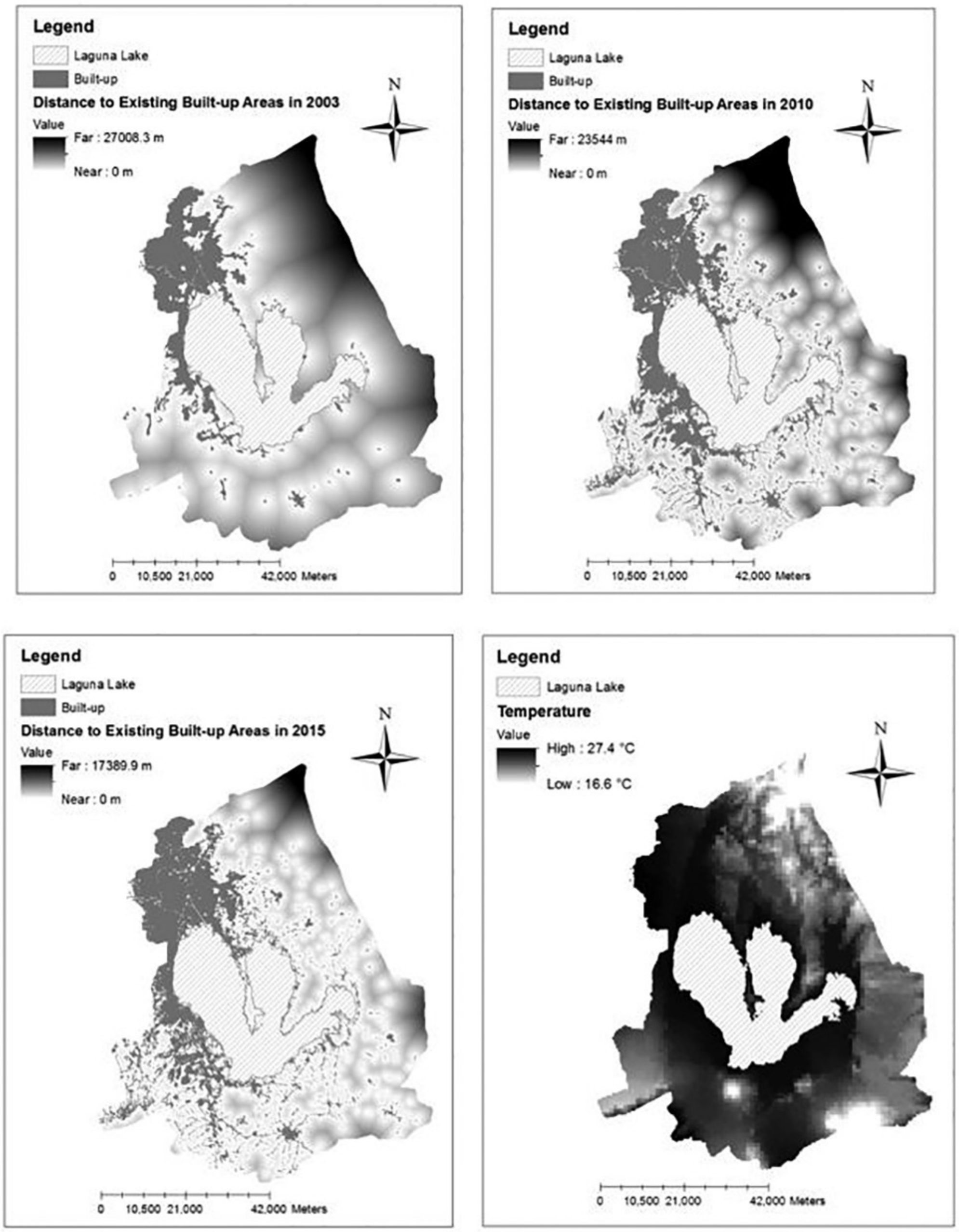

Figure A.3. From left to right, top row: (A) distance to existing built-up areas in 2003 and (B) distance to existing built-up areas in 2010; from left to right, bottom row: (C) distance to existing built-up areas in 2015 and (D) temperature [original built-up base maps from NAMRIA; temperature data processed from Hijmans *et al.* (2015)].

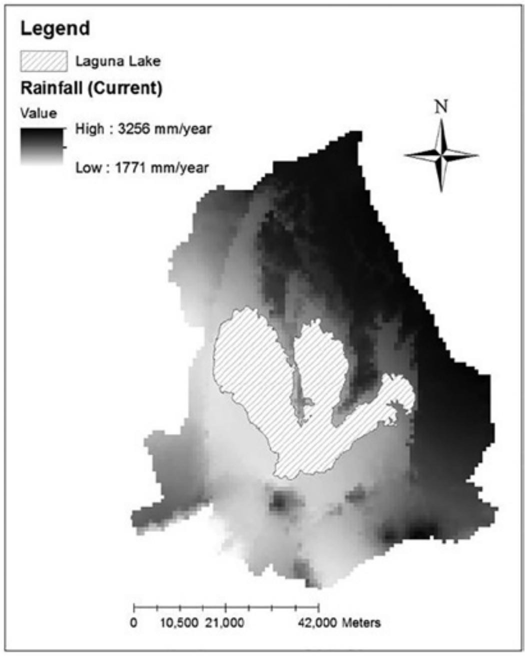

Figure A.4. Current rainfall driver map [rainfall data processed from Hijmans *et al.* (2015)].

An additional harmonized land cover map for 2010 is shown in Figure A.5.

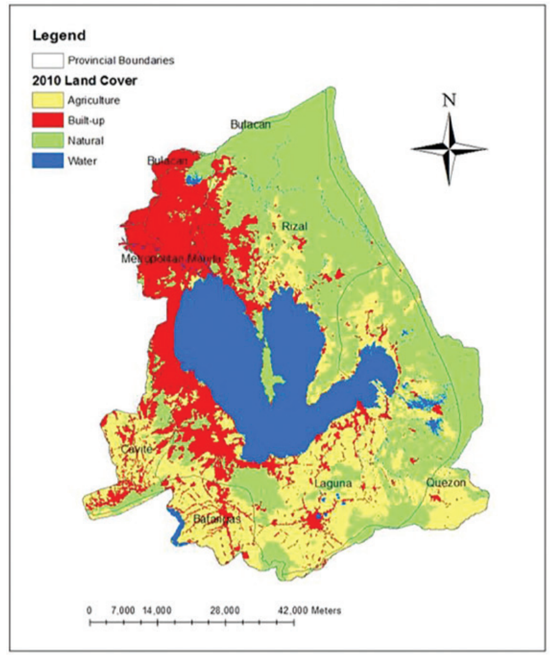

Figure A.5. 2010 harmonized land cover map [raw (unprocessed) land cover map obtained from NAMRIA; boundaries map from LLDA].

APPENDIX III

Additional Water Quality Data

This section discusses the water quality of Laguna Lake and its tributaries throughout the basin based on published secondary data by the LLDA. The water quality indicators monitored include nitrates, phosphates, chlorophyll, dissolved oxygen (DO), biological oxygen demand (BOD), and total coliform. Nitrates and phosphates are commonly found in runoff from fertilizer, livestock, and sewage. Major sources include agriculture (associated with agricultural land cover) and urban activities (associated with built-up land cover) (Carpenter 1998). Chlorophyll, measured as chlorophyll a for water quality indices, measures the amount of phytoplankton that causes eutrophication to occur, resulting in a higher BOD while lowering DO (LLDA 2013). High BOD levels are commonly associated with domestic wastewater effluent or septic tank leakage from built-up areas, and fertilizer runoff from agricultural areas (Brown 2001).

Laguna Lake is classified as Class C inland waters, which is appropriate for fisheries, irrigation, agriculture, and recreational water class II (*i.e.*, boating, fishing, *etc.*) under DAO 08, 2016. It is divided into West Bay, Central Bay, East Bay, and South Bay and is majorly used for fisheries. In the Laguna de Bay Report card released in 2013, the Laguna Lake Development Authority (LLDA) developed a system to measure and score the various water quality indicators (mentioned above) in relation to DENR guidelines regarding Class C waters. A system was also used to evaluate water quality in relation to its use, which is for fisheries. The indicators for this include zooplankton ratio, native fish species composition (*vs.* invasive species), and catch per unit effort (*i.e.*, average total daily catch *vs.* the total number of fishing hours) (LLDA 2013). The grading scale used for the evaluation can be seen in Figure A.6.

The lake was given an overall score, with individual scores given for West Bay, East Bay, Central Bay, and South Bay. In 2013, the Lake scored a C– (76%) overall in water quality because it did not meet the DENR guidelines for chlorophyll and phosphate levels (however, the levels for DO, BOD, nitrate, and total coliforms meet the guidelines). The lake also received an overall score of F (48%) for fisheries due to a large presence of invasive fish species and high competition for catch among fishermen. The individual scores for each bay are summarized in Table A.3.

East Bay scored highest in water quality but lowest in fisheries. While it received an A in almost all water quality indicators (the exception being chlorophyll, which was

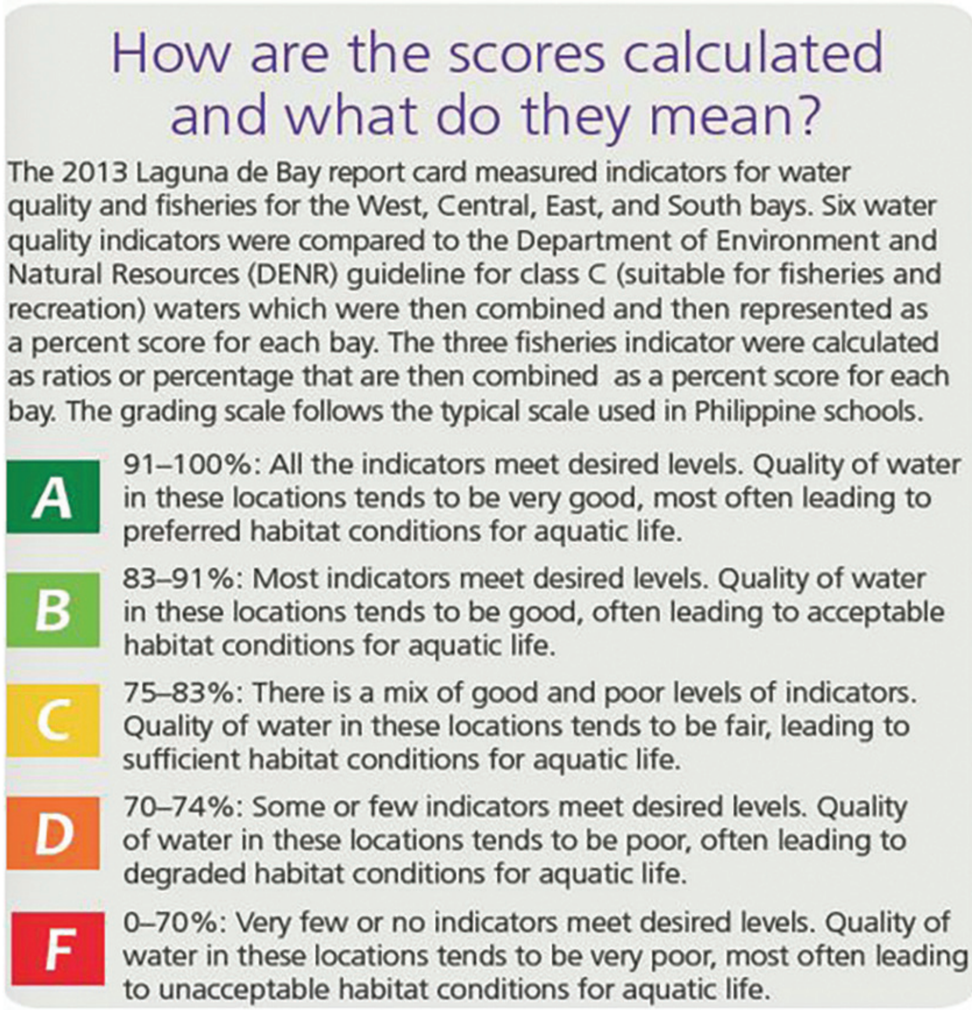

Figure A.6. Laguna de Bay report card scoring system (source: LLDA 2013).

Table A.3. Water quality and fisheries scores.

	Water quality score	Fisheries score
East bay	C+ (81%)	F (27%)
West bay	C– (76%)	F (55%)
Central bay	D (71%)	F (61%)
South bay	C (77%)	F (43%)

scored F), it also received an F in all fisheries indicators. This was due to East Bay being a smaller fishing ground with a high concentration of fishermen. It also contained the highest number of invasive species (the clown knife fish), which was suspected to be due to the good water quality in the area. West Bay received the second-to-the-lowest water quality score but was second-to-the-highest in its fisheries score (although it still was rated F). West Bay is the most developed and populated side of Laguna Lake, which is likely the reason for the poor water quality. The higher score in fisheries indicators was due to the presence of native fish species. West Bay also contains the highest concentration of fish pens and larger fishing ground. Central Bay had the lowest water quality score but scored highest in its fisheries score. Its low water quality score was due to a high concentration of phosphates and chlorophyll, while its high fisheries score was attributed to having the highest concentration of native fish in catch composition. South Bay received the second-highest water quality score due to scoring high in nitrate, DO, BOD, and total coliform criterion. However, it also scored second-lowest in fisheries because it had the lowest native fish species composition despite containing a fish sanctuary (LLDA 2013).

The poor water quality scores of Laguna Lake are of concern given that the LTM study predicted that most of the areas expected to transition to built-up lie along the lake's perimeter. West Bay, which scored poorly in water quality is also the area with the most built-up areas in the surrounding land. This includes Metropolitan Manila and the cities of San Pedro, Sta. Rosa, and Binan in Laguna, which are the more urbanized cities of the province. South Bay, which also received a low water quality score, is surrounded mostly by agricultural and built-up areas. East Bay, which scored the highest in water quality, is primarily surrounded by agricultural and natural land cover. This suggests that built-up areas are more likely to have an adverse effect on water quality. This is consistent with the findings of the Wealth Accounting and the Valuation of Ecosystem Services report, which showed that 80% of pollution loading in the lake comes from domestic waste (WAVES 2016). While the surrounding land cover of Central Bay was not as built-up as East Bay, intensive fishery activities in the area are likely the cause for its low water quality scores.

In the Annual Report of LLDA for 2015, data collected from the sampling stations positioned throughout the tributaries measured for BOD, DO, and coliform levels showed that not all tributaries met the criterion for Class C waters. Monthly BOD measured during the first half of 2014 showed that the tributaries of Tunasan-Upstream, Sta. Rosa-Upstream, San Juan, Los Baños, Bay, Pila, Sta. Cruz, Pagsanjan, Pangil-Upstream and Downstream, Siniloan, Sta. Maria-Upstream and Downstream, Pililla, and Tanay-Upstream and Downstream passed the standards for BOD. However, the tributaries Marikina, Bagumbayan, Buli, Mangangate- Downstream, Tunasan-Downstream, Binan, Sta. Rosa-Downstream, Cabuyao, San Cristobal, Manggahan Floodway, and Sapang-Baho did not meet the Class C standard for BOD. In terms of DO concentration, the report showed that the tributaries Bagumbayan, Mangangate, Tunasan, Cabuyao, San Cristobal, Floodway, and Sapang-Baho River consistently failed the Class C Criterion. The rivers of Sta. Rosa River-Upstream, Bay River, Pangil River-Downstream, and Tanay River-Upstream were the only tributaries to consistently meet Class C Criterion, while the remaining tributaries fluctuated between passing and failing the standards. In terms of total coliform, almost all tributaries exceeded Class C criterion with the only exceptions being Pangil River-Upstream in April, Sta. Maria River-Upstream in January and April, and Tanay River-Upstream in January (LLDA 2015).

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