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*Full Length Research Paper*

# Impact of urbanization on the morphology of Motoine/Ngong River Channel, Nairobi River basin, Kenya

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The geomorphic response of a stream to urbanization is a common interruption to the channel geometry equilibrium with dire consequences of sedimentation of reservoirs, mass wasting processes and water quality deterioration. The channel morphology was investigated with respect to deforestation, an increase in built-up surfaces and bank instability within the Motoine/Ngong River sub-catchment of the Nairobi River Basin in Kenya. The study examined the relation between growth of built-up surfaces and channel morphology at four representative sampling points along the course of the River for the period 1976 and 2013 for which there was sufficient record. The findings indicate a steady spatial increase of the built-up surfaces by 50.9% during the period. The impervious surface reduced infiltration capacity, simultaneously increasing surface runoff and stream flow and seasonal flow variability. The increased discharge caused bank erosion in some places and sedimentation in the others, a sinuous channel morphology characterized by river cliffs, river bank cavities, collapsing overhanging banks, tension cracks, slip-off slopes, sand bars and a braided river channel. The changing storage capacity of the Nairobi dam is currently unknown due to lack of instrumentation and hydrological records.

**Key words:** Watershed/catchment, urbanization, built-up surfaces, erosion, sedimentation, channel morphology, Motoine/Ngong River.

## INTRODUCTION

Urbanization is a pervasive and fast growing form of land use (Paul and Meyer, 2008) especially in developing countries as in Kenya. It is projected that more than 60% of the world's population will live in urban areas by 2030 (UN, 1997). The increasing population and rapid economic developments are key drivers of land use

change (Mundia and Aniya, 2006). Land use change is responsible for loss of vegetation cover, removal of soil cover and replacement with impervious surfaces, leveled slopes, increase housing density and other built infrastructures that generate impervious surface and artificial drainage channels.

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**Table 1.** The effect of land use sequence on relative sediment yield and channel stability.

Land use	Sediment yield	Channel stability
Cropping	Moderate to heavy	Some aggradation and increased bank erosion
Retirement of land from cropping	Low to moderate	Increasing stability
Urban construction - early phase	Very heavy	Rapid aggradation and some bank erosion
Stabilization and late phase of construction	Moderate	Degradation and severe bank erosion
Stable urban and limited construction	Low to moderate	Relatively stable

Source: Modified from Krhoda, 1986.

The hydrological consequences of urbanization include higher surface runoff, reduction of lag time between precipitation and runoff and increased peak flows and reduced low flows (Rose and Peters, 2001; Krhoda, 2002). Urban development results to an initial phase of sediment mobilization, characterized by increased sediment production and sedimentation within channels (Table 1; Chin, 2006). Watershed erosion supplies only about 25% of the sediment to a river channel system in contrast to bank erosion and bluff retreat that contribute 41% (Foyle and Norton, 2007). The rest of the sediment is contributed by bank erosion especially during floods (Zang et al., 2006). Drastic increase in channel sinuosity and braiding have been attributed to increased sediment discharge (Ahmed and Fawzi, 2009; Thakur et al., 2011).

The challenges of sediment control in Nairobi have been investigated (Krhoda, 1986), however the contribution of bank erosion to sedimentation in rivers have not been investigated before. It is also known that sedimentation aggravates severity of flooding. The presents study therefore investigates the impact of urbanization on channel erosion in Nairobi, Kenya. The study was carried out in Motoine/Ngong river sub-catchment.

**CATCHMENT CHARACTERISTICS OF THE STUDY AREA**

The study area is the Motoine/Ngong river sub-catchment covering an area of about 127 km<sup>2</sup> is part of the upper Athi River basin in Kenya. The river is 42.3 km long (Kahara, 2002), has its source from Motoine swamp near Dagoretti forest (Monene, 2014) and flows into the Nairobi Dam before becoming Ngong River (Figure 1). The Ngong River passes through Nairobi's Industrial Area before its confluence with Nairobi River. The basin falls under a wet climatic zone with a mean annual rainfall ranging from 1000 to 1200 mm (UNEP, 2003). The long rains come in mid-March to mid-May, and the short rains during the months of November and December. The wettest month is April for the long rains, with average monthly rainfall of approximately 223 mm. November records highest rainfall for the short rains at an average

of 166 mm. The driest months are August and September (FAO, CLIMWAT Database).

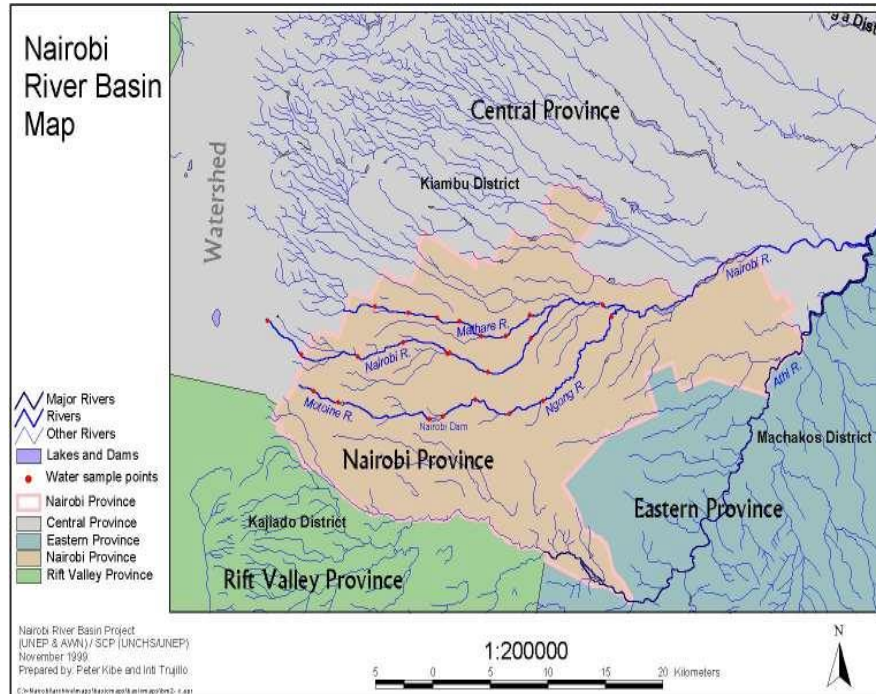
There are three major geological provinces within the study area. The upper part of the catchment flows over the Upper Athi volcanics which is porous and permeable thus allows percolation and as a result recharges the Motoine/Ngong River. The Lower Athi volcanics further downstream of the study area weathers in to clayey materials and therefore less conducive as an aquifer. The clay soils impede drainage and wherever slope decreases they form swamps. The third geological province, the Kirichwa Valley Tuffs, are exposed along the channel upstream of Nairobi dam. The rest of the catchment until Kangundo River Bridge is composed of deeply weathered Nairobi phonolites. Ngong river rises from an altitude of about 1,980 m a.s.l and drains into the Nairobi River at 1,525 m a.s.l (Krhoda, 2002). The catchment has a gentle slope of 1.01% except along specific channel sections where slopes range from about 7 to 19% (Figures 1 and 2).

The Motoine River rises from Riu Swamp and is heavily used in the settled Dagoretti area. As the river flows eastwards (mainly underground) for most of its course, farmers in the valley impound its water for irrigation agriculture and domestic uses. The Motoine River starts receiving agrochemical pollution right from its head water in the Dagoretti area (sediments, dairy and abattoirs), and picks other forms of pollution as it flows through the Ngong Forest and the Kibera area. The soils exposed along the channel banks are generally dark grayish brown to very dark grayish brown clay, vertisols, with a high shrink-swell potential.

**METHODOLOGY**

Primary data collection was done during a field survey to measure river discharge, channel geometry, and identify erosion features in 2012. Discharges were measured using a current meter OTT C2 at 4 representative river cross sections at Motoine swamp outlet, Ngong Road Bridge, Dam inlet and Kangundo Bridge.

$$Q_r = \sum_{t=1}^n A_c V_i \tag{1}$$



**Figure 1.** Basic map of Nairobi River Basin and surrounding provinces. Source: Khoda, 2002. Nairobi River project Phase 1, UNEP/ROA, Nairobi.



**Figure 2.** Informal farming within the basin. Source: Khoda, 2002. Nairobi River project Phase 1, UNEP/ROA, Nairobi.

Where:  $Q_r$  is the river discharge;  $A_{c_i}$  is the river cross section ( $m^2$ );  $V$  is the cross sectional velocity;  $i$  denotes any measurement in the series of velocity or cross sectional area.

Further information on historical perspective relating to land use change and floods occurrence were obtained by administering a structured questionnaire. Statistical measures of central tendencies, correlation analysis and calculation of percentages were used to determine temporal and spatial changes in land use and channel characteristics. Suspended sediments samples were collected during the rainy seasons at each cross section with discharge measurements. Sediment discharge was determined using the expression:

$$Q_s = Q_w \cdot C_s \cdot K \tag{2}$$

Where:  $Q_s$  is sediment discharge;  $Q_w$  is water discharge;  $K$  is a constant.

There was little discharge during the dry seasons. Secondary data was obtained from topographical maps covering the basin with a scale of 1:50,000 while geological and soil information was obtained from maps. Socio-economic and population data were obtained from census report (1999). Additional data on changes in land use were obtained from satellite imageries for the years 1976, 1984, 1995, 2002 and 2013 from the Department of Resources



**Table 2.** Land use changes from 1976-2013.

Land cover (%)	1976	1984	1995	2002	2013
Wetland	0.24	0.24	0.24	0	0
Bare ground	57.48	18.44	3.25	32.54	23.86
Grassland	2.14	7.59	10.84	0.54	1.3
Forest	15.18	6.50	8.68	7.59	8.68
Other vegetation	2.17	35.79	34.70	14.86	15.18
Built up area and road	22.78	31.45	42.30	44.47	50.98

Source: Monene, (2014).

Surveys and Remote Sensing (DRSRS).

**RESULTS AND DISCUSSION**

**Land use changes between 1976 to 2013**

Nairobi City has grown at a rate of 3.7% per annum since 2003 compared to 60% in the early 1960s (UNEP/ UNHABITAT/GOK/NCC, no date). The spatial change of land use/land cover between 1976 to 2013 in Motoine/ Ngong river sub-catchment is shown in Table 2. The areas covered by wetland, bare ground, grassland and forest have seen remarkable decrease in the 37 years of record. Apart from built-up surfaces the other land use patterns in the sub-catchment were bare ground, grassland, forest and other vegetation. Other vegetation pattern of land use registered an increase as well from 2.17% in 1976 to 15.18% in 2013, an increase of 600% reflecting dynamics of urban growth and land use change. Between 1984 and 2000 a large population migrated in to Nairobi City and grassland and bush were cleared to settle in the lower part of the study area. Similarly large parts of Ngong Road forest were cleared for road construction, development of schools, churches, public cemeteries and other social facilities. The built-up surfaces within the sub-catchment increased from 22.7% in 1976 to 50.9% in 2013, an increase of 124%. Mundia and Aniya (2006) attributed such changes in land use to population growth and rapid economic development of Nairobi. Increase in built-up surfaces and reduction of grassland and forest cover increase surface runoff and erosion. The hydrological implication is that as land cover is removed and replaced by pavements, the storm runoff is expected to increase, sediment transport will increase and channel geometry will change.

**Water balance of Nairobi Dam**

The Nairobi Dam was constructed in the late 1940's as a source of fresh drinking water for the city of Nairobi. The poundage stabilized the flood flows of the river thus impacting on channel geometry. However, over the past

decades the dam has reached hypereutrophic levels and is generally of little hydrologic and socio-economic impacts. The dam is nevertheless an essential part of the river course. The water balance of the dam has been estimated from the annual rainfall, using the expression:

$$R = R_o + E_p + dS \tag{3}$$

Where: R: rainfall (mm), R<sub>o</sub>: Runoff, E<sub>p</sub>: Evapotranspiration, dS: Change in water storage.

The annual rainfall estimated from the isohyets over dam is about 875 mm while the surface area of the dam is 356,179 m<sup>2</sup>. The total contribution of rainfall to the dam is 311,656m<sup>3</sup> per year. The evaporation rate is about 1750 mm per annum. Evapotranspiration from the water hyacinth (*Eichhornia crassipes*, which is native to the Amazon basin, Brazil) may be higher than potential evaporation and has been estimated at 3 to 4 times the rate of potential evaporation (Van den Weert and Kimmerling, 1974). The total water loss as a result of evapotranspiration is about 711,289 m<sup>3</sup> per annum. The loss of storage possibly has influenced the channel adjustment over the years.

**River channel changes due to urbanization**

Stream morphology reflects the balance between erosion and deposition processes induced by geology, gradient and energy of flow at differing flow stages. The Motoine river channel is narrow, crosses a seasonal swamp and flows over a flat section in its most upstream section. It is crossed by two bridges namely at Ngong Road and the Kangundo Road. At Bridge 1 a well cut-out channel valley and initial meanders along its course begin to form. Channel incision accompanied by increased runoff causes a deep and steep meandering channel with outcrop rocks on its bed at the Nairobi dam inlet. The valley consequently widens at the Bridge 2 and the wide and deep channel with meanders and braids form as the gradient decreases from 19% to between 10%. The mean of the study reach is 14.5%.

From the weir of the Nairobi Dam downstream the river channel is for the most part channelized as it flows

through the Industrial area. Runoff from the impervious surfaces such as iron sheet roofs of the Kibera settlement as shown Figure 3 and the new Ayany Highrise Towers (Figure 4) contribute significant amounts of roof runoff into the river especially during rainstorms. During dry seasons, the amount leaving the dam through the spillway becomes a mere trickle, but when there are heavy rains, it floods. In November 2001, the flow from spillway was measured at  $0.2 \text{ m}^3/\text{s}$ . These processes result to development of very steep banks or cliffs. Watson and Basher (2006) found that undercutting occurs as a result of redirection and acceleration of flow around obstructions such as debris and vegetation within the channel.

### Erosion of the River Banks

River bank erosion is a natural geomorphic process which occurs in all channels as they adjust their size and shape to convey the discharge and sediment supplied from the catchment. Accelerated river bank erosion is often associated with land use change. According to Watson and Basher, (2006) river bank erosion processes are classified into two, those dominated by gravitational failure (mass movement and individual grain failures) and those where hydraulic-induced failure mechanism (fluvial erosion) dominates. The mass movement and fluvial erosion are often linked and both were observed along the Motoine/Ngong river channel particularly at and around Kangundo Road Bridge. These processes or mechanisms of slope instability, operate on the bank either simultaneously or sequentially (Thorne and Furbish, 1995). The hydraulic processes at or below the water surface entrain sediment and directly contribute to erosion, involving bank undercutting, and basal cleanout and gravitational mass failure processes (including shallow and rotational slides, slab failures, earth flows and dry granular flows).

### Gravitational mass failure processes

Prolonged rainfall events cause strength reduction and increase in unit weight of the materials causing the channel banks to collapse. Gray and Sotir (1996) noted failures occurring when the erosion of the bank and the bed adjacent to the bank have increased the slope angle to a point where it reaches a condition of limiting stability. Localized erosion of joint filling material, or zones of weathered rock, can effectively decrease interlocking between adjacent soil blocks thus significantly reducing the soil shear strength. The resulting decrease in shear strength may allow a previously stable soil mass to move causing slope failure. In addition, localized erosion may also result in increased permeability and ground-water flow thus affecting the stability of rock slope.



Figure 3. Housing in Kibera informal settlement.



Figure 4. The Ayany Highrise housing scheme in Kibera Area.

The shear strength of a soil mass is the internal resistance per unit area that the soil mass can offer to resist failure and sliding along any plane inside it. Shear strength is a term used in soil mechanics to describe the magnitude of the shear stress that a soil can sustain. On the other hand, shear resistance of soil is a result of friction and interlocking of particles, and possibly cementation or bonding at particle contacts. Rate of loading, degree of compaction, density and moisture content of the soil materials also affect its slope stability. Amongst these factors, moisture content appear to be the most significant in that water forms bridges between sand grains resulting in negative pore pressure. Permeability of the soil affects seepage pattern and water levels in the slope. This, in turn, can affect shear resistance of the material depending on the size and shapes of the particles, degree of compaction and the gradation of soil and its density (Aubeny and Lytton, 2004). Due to interlocking, particulate material may expand or contract

in volume as it is subject to shear strains. If soil expands its volume, the density of particles will decrease and the strength will decrease; in this case, the peak strength would be followed by a reduction of shear stress. The functional relationship between normal stress and shear stress on a failure plane can be expressed in the following form:

$$\tau_f = f(\sigma) \tag{4}$$

The failure envelope defined by Equation 4 is a curved line. For most soil mechanics problems, it is sufficient to approximate the shear stress on the failure plane as a linear function of the normal stress. The relationship between the peak shear strength  $\tau$  and the normal stress,  $\sigma$ , can be represented by the Mohr-Coulomb equation in the form:

$$\tau_f = c + \sigma \tan \phi \tag{5}$$

Where:  $c$ : cohesive strength, resistance per unit area,  $\phi$ : angle of internal friction,  $\sigma$ : normal stress on the failure plane,  $\tau_f$ : shear strength.

The average normal inter-granular contact force per unit area is called the effective stress. In saturated soil, the total normal stress at a point is the sum of the effective stress ( $\sigma'$ ) and pore water pressure ( $u$ ), or

$$\sigma = \sigma' + u \tag{6}$$

The volume change behavior and inter-particle friction depend on the density of the particles, the inter-granular contact forces, and to a somewhat lesser extent, other factors such as the rate of shearing and the direction of the shear stress. The soil is free to dilate or contract during shear if the soil is drained. In reality, soil is partially drained, somewhere between the perfectly undrained and drained idealized conditions. The shear strength of soil depends on the effective stress, the drainage conditions, the density of the particles, the rate of strain, and the direction of the strain.

When soil expands its volume, density of particles and the shear strength will decrease. The shear strength of soil depends on the effective stress, the drainage conditions, the density of the particles, the rate of strain, and the direction of the strain. Slope failure occurs in high bluffs and contribute to bank erosion through the process of undercutting and removal of the toe material along the channel bank (Kiss et al., 2013). The most critical condition is strength reduction due to rapid drawdown after a high flow stage exceed the resisting forces. The resisting forces are related to shear strength of the bank materials, and expressed by Fredlund et al. (1978) as:

$$\tau_o = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \tag{7}$$

Where:  $\tau_o$  = shear strength (kPa),  $c'$  = effective cohesion (kPa),  $\sigma$  = normal stress (kPa),  $u_a$  = pore air pressure

(kPa),  $\phi'$  = friction angle in terms of effective stress (degrees),  $u_w$  = pore water pressure (kPa),  $\phi^b$  = angle representing the rate of strength relative to friction.

The angle  $\phi'$  ranges between 11° and 30° with a mean of 18°. Stream flow variability causes frequent refreshing of channel bar surfaces, sometimes bar destruction and re-formation removes or minimizes vegetation on bar surfaces (Fuller, 2007). Instead the presence of vegetation cover on channel bars are indicators of channel stability and limited erosive capacity. The present research therefore investigates river channel morphology resulting from an urbanization process over the last 37 years and suggests necessary steps for land use management and river channel restoration.

The variation of strength characteristics of black clays across the study area would be reflected by the distribution of shear strength parameter, ( $\phi'$ ). Soil depths of less than 0.50 m are characterized by relatively higher maximum (30°), minimum (16°) and mean (21°) values; than those of 0.50 m depth and greater which have maximum, minimum and mean values of 23°, 11° and 17°, respectively.

Increasing moisture content of clay-like soil turn them to sticky mud and reduces the soil's shear resistance to sliding. The soil Liquid Limit (LL) is defined as the moisture content above which the soil behaves as a liquid, and the Plastic Limit (PL) is the moisture content above which the soil behaves plastically. The numerical difference between the Liquid Limit and Plastic Limit is termed the Plasticity Index (PI). The plasticity index (PI) is the size of the range of water contents where the soil exhibits plastic properties. The PI is the difference between the liquid limit and the plastic limit;

$$PI = LL - PL \tag{8}$$

Where: PL is the Plastic Limit, and LL is the Liquid Limit.

$$PL = (\text{mass of water} / \text{mass of oven-dry soil}) \times 100 \tag{9}$$

Using the British Standard relationship (BS 1377: 1967), that is,

$$PI = 2.13 * LS \tag{10}$$

Where: LS is Liquid clays, values ranging between 21 and 29% for clays.

According to Johnson and De Graff (1988), the shear strength of soils is usually inversely proportional to their plasticity. As a result, the observed slight decrease of strength characteristics of black clays with depth could be attributed to a corresponding slight increase of their plasticity (PI) with depth. Published laboratory test results indicate that the plasticity range of vertisolic soils typically found in the middle and lower catchment range between 25 and 45% and the Liquid Limit (LL) is between 50 and 70 (USDA, Soil Conservation Service, 1971. Guide for

Interpreting Engineering Uses of Soils, Washington, D.C., 86 p).

### Hydraulic processes

In the first type, erosion changes the geometry of the potentially unstable bank by removal of material at the toe of the bank and reduces the confining stress that may be stabilizing the slope. Photogrammetry survey immediately after the slab failure revealed that collapse of overhanging blocks of undercut river banks depended on bank height and angle of slope. The critical height of slope depends on shear strength, density and bearing capacity of the slope foundation. Slope stability generally decreases with increase in height of slope. As the slope height increases, the shear stress within toe of slope increases due to added weight. Shear stress is also related to the mass of the material and the slope angle. With increasing slope angle, the tangential stress increases which result in increase in shear stress thus reducing slope stability.

Key factors that cause undercutting of river banks are discharge, characteristics of bank material and local soil moisture condition (Thorne and Furbish, 1995). Erosion processes of river banks occur as a result of direct removal of bank materials by the shearing action of flow. Once they were undercut the overhanging upper parts of the river bank becomes unstable. These overhanging upper parts eventually collapse into the river. This is aided by mass wasting that occurred as a result of undercutting of the river banks under the influence of gravity (Figures 5 and 6). Widening of the river channel (Kiss et al., 2013; Nasermoaddeli and Pasche, 1998) found that undercutting of the river banks, avalanche of the submerged zone of the river bank and failure of the overhang were dominant processes on non-cohesive river banks. The vertisols and vertic gleysols and the channel banks are planted Napier grass, maize, beans and a variety of vegetables. For this reason, the river banks have been undercut, the soils have desiccation or tension cracks and frequently collapses in to the channel. Undercutting was prevalent along river bends. Velocities decrease closer to the outer bank and near the bed of the channel.

### Slab failure

Slab failure involves sliding and forward toppling of a deep seated mass into a channel along stress (dessionation) cracks (Merz, 2010) which occur during the preceding dry period (Figure 7). Other sections where the cracks had progressed lost resistance and had collapsed into the channel (Figures 8). The slab failure occurs on a steep, low height, clay bank during low flow conditions (Watson and Basher, 2006). The process are rather



**Figure 5.** Land slide of high river cliffs. Source: Monene, 2014: Pictures taken on 17/12/13 and 5/9/13.



**Figure 6.** Collapsing of banks. Source: Monene, 2014: Pictures taken on 17/12/13 and 5/9/13.



**Figure 7.** Unstable outer bank showing cracks. Monene, 2014: Photographs were taken 10 m downstream of Kangundo Road Bridge on 17/12/2013.



**Figure 8.** Collapsed outer bank. Monene, 2014: Photographs were taken 10 m downstream of Kangundo Road Bridge on 17/12/2013.



**Figure 10.** Basal Cleanout of the outer bank. Monene, 2014: Photographs were taken near Kangundo Road Bridge on 28/12/2012.



**Figure 9.** Basal Cleanout of the inner bank. Monene, 2014: Photographs were taken near Kangundo Road Bridge on 28/12/2012.

complex thus combining scour at the bank toe, high pore-water pressure along the bank material and the development of tension cracks at the top of the bank. An accumulation of failed loose blocks that seemed to offer temporary protection to the lower section of the river bank were soon washed away (Figures 9 and 10).

Decreasing bank resistance to erosion were caused by rapid drawdown of water levels after a rainfall event, consistent lowering of the water table during the dry season, existence of erodible river banks and desiccation of the river bank material. During dry weather the soil loses moisture and contracts. It is during contraction that cracks develop in the soil and subsequently collapse into the river. During the wet season the clay soils absorb moisture and expand. The cracks were on the outer bank

of the river, were about 2 m deep and seemed quite unstable. The collapse of these unstable blocks results to erosion of banks, exposes a new surface to erosion, causes soil loss and supplies sediments to the river.

Some points of the river banks portrayed basal cleanout as they had been freshly swept clear of loose soil particles. Direct observation and photography revealed that flash floods had removed supportive and protective bank material, either vegetation or loose soil particles and uprooted vegetation that had colonised the river banks. It was noted that the removal of collapsed bank material left the lower river bank material exposed to a continuous cycle of undercutting, collapse and removal, and the subsequent transportational process thus widening the bank especially during the rainy seasons. Friedman and Lee (2002) found that channel widening was dominant process occurring within hours during infrequent floods.

**Cavitation process**

Cavitation is an erosion process involving air bubbles trapped in the water that get compressed into small spaces like cracks in the river’s banks. These bubbles eventually implode creating a small shockwave that weakens the bank materials. The shockwaves are very weak but over time the materials will be weakened to the point at which they fall apart. The bank consist of fine-grained cohesive loamy sands materials. River bank cavities or pop out failure were observed near the base of the river bank at about 100m upstream of Bridge 2 (Figures 11 and 12) along a steep inner bank. The cavities occurred at the middle and lower parts of the banks which imply that secondary circulation. The bridge causes channel constriction creating backwater effect that likely generates secondary circulation thus causing



**Figure 11.** Undercutting of outer bank. Source: Monene 2014: Photos taken on 17/12/2013 during wet season) and 5/9/2013 during dry season.



**Figure 13.** Dry season channel braids.



**Figure 12.** Pop out failure results to cavities. Source: Monene 2014: Photos taken on 17/12/2013 during wet season) and 5/9/2013 during dry season.



**Figure 14.** Wet season channel braids.

additional pressure on the banks. As earlier discussed flow of Motoine/Ngong river varies between seasons and flash floods rise and fall rapidly after a rainfall event. The pore pressure along the river banks caused small to medium sized blocks of fine grained cohesive material to fall out leaving a cavity. The fine cohesive materials allow the buildup of positive pore water pressure and strong seepage within its structure causing the roof of the cavity to collapse resulting to river bank retreat.

### Channel braiding and bars

Channel braiding is a reflection of increased sediment discharge or reduction in discharge and hence sedimentation within the channel. Motoine/Ngong River, downstream the Kangundo road Bridge, has channel bars that get eroded and disappear at high flow stages. The channel is braided downstream the Bridge 2 (Figures 13 and 14). Church and Jones (1982) found that at higher flow stages the largest volumes of sediment are transported and the channels are scoured. During the falling stage maximum deposition occurs as discharge and flow competence are reduced. The channel bed

aggrades and the bar emerges. The channel constriction at the bridge no. 2 after which the water spreads out, channel width increases, and depth decreases. The bar surfaces have vegetation indicative that the bars are stabilizing. The bar separating the channels was larger during the dry season than during the rainy season. The bar disappeared at high flow stages and reformed as discharge fell.

The bars at Motoine/Ngong river had no vegetation. This implies that there is frequent refreshing of bar surfaces, bar destruction and re-formation. This means there is increased erosion and flood frequency and magnitude. Presence of vegetation indicates a degree of stability. Material composition of the bar varies between seasons. The dry season bar was composed of finer materials. During the rainy season the fine materials forming the bar had been eroded by flash waters, leaving behind boulders.

**Channel bed deformation process**

Previous studies reveal that the processes of bed degradation and lateral erosion destabilize the upper part of the bank (Figure 15). The role of basal erosion is to reshape bank geometry by entraining sediment from the submerged portion of the bank surface when the flow shear stress is greater than the bank resistance force. Basal erosion steepens the bank surface by fluvial undercutting at the bank toe. Consequently, bank failure such as planar, toppling and cantilever, occurs depending on various failure mechanics of cohesive or non-cohesive soil. Outer bank experiences additional pressure caused by the centrifugal force of the current in a bend.

**Rocky outcrops**

As slope decreases the volcanic rock outcrops emerge showing that further channel incision has been curtailed (Figure 16). In this respect, the appropriate channel response to increased discharge is basically flooding, a feature characteristic of the lower part of the basin.

**Conclusions**

There has been spatial change in land use in Motoine/Ngong River sub-catchment during the period of study. The change was characterized by both increase and decrease of the area covered by respectively the forest, grassland and bare ground. During the study period the coverage by wetland, bare ground, grassland and forest were lower in 2013 than in 1976 and together these cover 75.04 of the catchment in 1976 but only 33.84% in 2013. Built up area and road surfaces was the only pattern that recorded a steady increase from 22.78% in 1976 to



**Figure 15.** Channel meanders. Monene, 2014: Photos taken on 17/12/2013 and 5/9/2013 respectively.



**Figure 16.** Outcrop rocks near dam inlet. Monene, 2014: Photos taken on 17/12/2013 and 5/9/2013 respectively.

50.98% in 2013. The other vegetation types increased and decreased according to the dynamics of land use in the catchment. There has been spatial increase in built-up surfaces from 1976 to reach 50.9% of the catchment in 2013. The increase in impervious surface cover reduces infiltration while increasing surface run-off and stream flow. Erosion and sedimentation resulting from flow variability are associated with rainfall events. Channel morphology characterized by meanders, braiding, river cliffs, river bank cavities, collapsing overhanging banks, tension cracks, slip-off slopes sand bars have been associated with changes in land use and stream flow

variability.

### Conflict of Interests

The authors have not declared any conflict of interests.

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### REFERENCES

- Ahmed AA Fawzi A (2009). Meandering & Bank Erosion of the River Nile and its Environmental Impact on the Area between Sohag and El-Minia, Egypt. *Arab J. Geosci.* 4:1-11.
- Aubeny CP Lytton RL (2004). Shallow slides in compacted high plasticity clay slopes, *ASCE J. Geotech. Geoenviron. Engng.* pp. 717-727.
- Chin A (2006). Urban Transformation of River Landscapes in a Global Context. [www.sciencedirect.com](http://www.sciencedirect.com).
- Church M, Jones D (1982). Channel bars in Gravel bed Rivers. *Gravel bed Rivers*, Wiley, Chichester. pp. 291-338.
- FAO Database, CLIMWAT 2.0 for CROPWAT, Water Development and Management Unit.
- Friedman JM, Lee, VJ (2002). Extreme Floods, Channel Change and Riparian Forests along Ephemeral Streams, *Ecol. Monographs* 72(3):409-425.
- Fuller I (2007). River and Channel Morphology: Measuring and Monitoring Channel Morphology. School of People, Environment and Planning, Massey University, New Zealand.
- Kahara J (2002). Nairobi River Basin Project Phase III, United Nations Environment Programme.
- Kiss T, Blanka V, Andrasi G Hernesz P (2013). Extreme Weather and Rivers of Hungary: Rates of Bank Retreat. *Geomorphological Impacts of Extreme Weather: Case Studies from Central and Eastern Europe*. Springer Science & Business Media.
- Krhoda G (1986) Problems of sediment control and management in urban areas. In: Thomas, DB et al, *Soil and Water Conservation in Kenya*. Proceedings of the 3rd National Workshop, 16-19 Sept.
- Krhoda G (2002) Nairobi River Basin Project Phase III, UNEP.
- Merz SK (2010). Study of River Bank Collapsing-Lower River Murray, Inspection  
[https://www.waterconnect.sa.gov.au/Content/Publications/DEWNR/Riverbank\\_Collapse\\_Geotechnical\\_Investigation\\_Phase\\_3\\_SKM\\_2009.pdf](https://www.waterconnect.sa.gov.au/Content/Publications/DEWNR/Riverbank_Collapse_Geotechnical_Investigation_Phase_3_SKM_2009.pdf)
- Monene AK (2014). Effects of Land Use Change on Stream flow, Channel Erosion and River Geomorphology: A Case Study of Motoine/Ngong River Sub Catchment. Unpublished M.A. thesis, Department of Geography and Environmental Studies, University of Nairobi.
- Mundia CN Aniya M (2006). Dynamics of Land Use/Cover Changes and Degradation of Nairobi City, Kenya. *Land Degrad. Dev.* Wiley Online Library, 17(1):97-108.
- Rose S, Peters NE (2001). Effects of Urbanization on Stream Flow in Atlanta Area, USA. *Hydrol. Process.* 15:1441-1457.
- Thakur PK., Laha C, Aggarwal SP (2011). River Bank Erosion Hazard Study of River Ganges, Upstream of Farakka Barrage Using Remote Sensing and GIS. *Nat. Hazards* 61:967-987.
- UNEP (2003). The Nairobi River Basin Project – Phase III. Resource Booklet on Pollution Monitoring Activities.
- Van den Weert, Kimmerling GG (1974). Evapotranspiration of water hyacinth. *J. Hydro.* 22:201-212.



*Full Length Research Paper*

# Land-use suitability analysis for urban development in Regional Victoria: A case study of Bendigo

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**Selection of suitable areas for urban development is a complex process and needs many diverse indications on the basis of which decision may be assumed. The aim of this study is to examine the GIS-based land-use suitability analysis and its application in urban planning decision making, using Bendigo, a regional city in Victoria as a case study. The objective of this study is to provide evidence-based solutions to urban growth management issues in regional Victoria. Bendigo is a major regional municipality of Victoria, including Bendigo city and surrounding rural hinterland, with six smaller townships scattered across the region. Greater Bendigo boasts of large areas of national parks, reserves and bushland, as well as agriculture land, which is the major land use of the area. This region has been earmarked by the Victorian Government's Initiative Urban Development Plan for future development as one of Victoria's regional centres for increased development and new homes. Geophysical, socio-economic and cultural data are used to assess future urban growth suitability in Bendigo based on key goals such as Connected and Compact City (transport and connectivity), City of Equality (education, health services), Ecological City (environmental conservation), and Safe City (risk of disasters). The resultant suitability map indicates primary suitable lands for future urban growth are located adjacent to the established urban areas. Reflecting the current urban development in Bendigo, the paper concludes with several recommendations aimed at improving the long-term urban development plans for the Greater Bendigo area.**

**Key words:** Land use, suitability analysis, Victoria, Bendigo

## INTRODUCTION

Sustainable development has been embedded into the global agenda of urban and landscape planning since Rio Summit in 1992 (Graymore et al., 2009). One specific challenge facing sustainability in the built environment sector is the global increase in urbanization (Childers et

al., 2014). Despite continuous efforts of generations of planners, designers and developers, building sustainable communities remains a challenge to academics and practitioners in the urban and regional planning discipline. The increasingly interlinked political, military, economic,

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technological, cultural, ecological and social issues across all scales have only exacerbated the already highly fragile and fragmented habitat for sustainability, physical or intellectual, on the planet. On the one hand, there are no acknowledged tools or approaches that can guarantee sustainable outcomes of urban development projects, on the other hand, numerous houses and communities are being built every day. This dilemma calls upon a sound approach to guide urban planning and development practice so that societal sustainability would not remain a dream. This study aspires to examine the potential of land-use suitability analysis in support of sound and rationale decision-making in urban planning and development aiming at more sustainable design outcomes.

More than 90% of Australia's population lives in cities and urban population in Austria keeps growing (Trading Economics, 2014) and is predicted to grow in the future. From 2011 to 2016, Victoria in Future 2008 projections indicate that the average annual dwelling demand across the municipal area of Greater Bendigo will be 999; from 2016 to 2021, increasing to 1,009 per annum. Victoria in Future 2008 based demand projections over the next 5 years for Greater Bendigo indicate that the current levels of dwelling construction activity are insufficient to meet potential demand. These demand projections are 29% greater than recent building approval activity (average 775 dwellings per annum between 2005/06 to 2008/09) and 92% greater than recent residential lot construction (average 518 lots constructed per annum between 2005/06 to 2008/09). In total (excluding existing vacant residential lots), there is a residential lot supply of approximately 18,500 (Department of Planning and Community Development (DPCD), 2010a). As a relatively small and self-contained city, Bendigo makes a good case study to understand the interplay of the pressure to provide quality housing for citizens and the challenges to deliver sustainable development. Using Bendigo as an example, the aim of this study is to explore opportunities for innovate planning approaches, by examining the GIS-based land-use suitability analysis approach and its application in urban planning decision making. The objective of this study is to provide evidence-based solutions to urban growth management in Bendigo. It is hoped that the experience of Bendigo could also provide useful reference for other rapid urbanising cities and towns in Victoria.

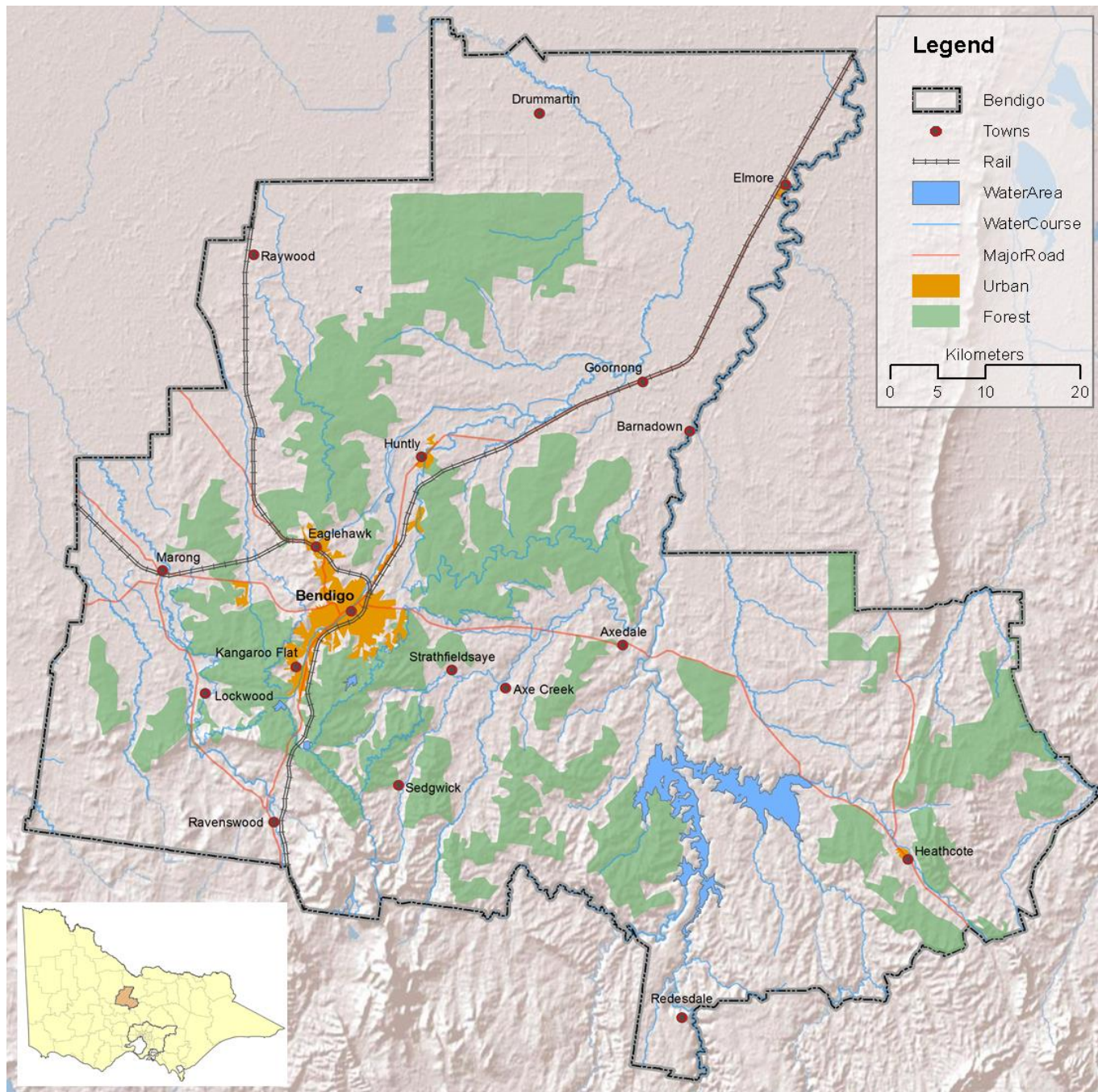
## LITERATURE REVIEW

Land-use suitability analysis integrating Geographical Information Systems (GIS) and multi-criteria decision analysis to evaluate the potential of converting current land use to urban development according to special requirement is one of the most useful applications for

sustainable urban development and planning (Malczewski, 2004; 2006) by minimising negative impact of urban development on the land system. In association with multi-criteria decision analysis (MCDA), GIS is used as a powerful tool in the process that integrates and transforms geographic data (input criteria) and value judgments (decision makers' preferences) to obtain an overall assessment for choosing between alternative actions or ranking prioritised suitable lands for proposed land uses (Malczewski, 2004). Recently, spatially explicit land-use suitability modeling using GIS has been increasingly used as a technique for landscape evaluation and planning (Girvetz et al., 2008), regional planning and environmental impact assessment (Marull et al., 2007; Rojas et al., 2013) and identification of potential locations for renewable energy generation (Angelis-Dimakis et al., 2011; Ramachandra and Shruthi, 2007), and evaluation different sites for future urban development (Joerin et al., 2001; Steiner et al., 2000). This study pays special attention to the use of land use GIS and multi-criteria decision analysis methods for developing maps of urban development priorities in the City of Greater Bendigo.

## The City of Greater Bendigo

Located 150 km northwest of Melbourne (Figure 1), Bendigo's initial rapid expansion, both economically and socially, was fuelled by the discovery of gold deposits in the 1850s. The wealth generated from the mining of gold was considerable, resulting in an architectural legacy that is reflected in the number of historic buildings that characterise the inner city area. With an existing population of 110,579 and an expected growth of 41.21% between 2015 and 2036 (Forecast.id, 2015), Bendigo is considered one of the key regional centres to accommodate future population growth and progress within the state of Victoria (DPCD, 2010b). However, history reveals that growth in Bendigo has not been constant. The first European settlements in Bendigo were mainly induced by the Gold Rush era in the 1850s which contributed to the state and the nation's development and influenced migration from countries such as China, India, Indonesia, Malaysia, Japan, and Germany (Carthew and Allan, 2005). On the one hand, the rich history of Bendigo stimulated the emergence of industries and alternative economic activities in the city and broader urban region from the mid-19<sup>th</sup> century to the mid-20<sup>th</sup> century (City of Greater Bendigo, 2005). On the other hand, from the 1960s to 1980s Bendigo experienced a slow growth satisfying the requirements of a rural area (Carthew and Allan, 2005). In the twentieth century the manufacturing sector developed as the gold deposits were depleted, but in more recent years the service sector, particularly retail, health, education and tourism, has become more prominent and brings new vitality to the livelihood of the



**Figure 1.** Location, context, and geophysical condition of City of Greater Bendigo.

region (DPCD, 2010b). Needless to say, sustainability integrating economic development with the characteristics of the local geography and vernacular landscape is the key to maintain and enrich the long-term liveability and prosperity of the Bendigo region.

The City of Greater Bendigo has recently adopted the Greater Bendigo Residential Strategy as a key strategy for managing urban growth from 2014 to 2034. This

strategy has been drafted in response to projected urban growth and on-going diversification of Bendigo's economy (City of Greater Bendigo, 2015). Importantly, there is increasing community support and desire for planning goals and strategies towards diverse healthy communities and transit-oriented development alongside increased demand for smaller lots and infill development in established areas (DPCD, 2010b; City of Greater Bendigo,

2015). The Greater Bendigo Residential Strategy contains a number of key policy directions mirroring these goals, of several which are significant, such as the strengthening of the Bendigo Urban Growth Boundary (UGB) - underlining its mandate within the community of Greater Bendigo. On a practical statutory level, the Greater Bendigo Residential Strategy will be implemented through the Greater Bendigo Planning Scheme Amendment C215 (City of Greater Bendigo, 2015).

Despite all these visions and aspirations aimed at transforming City of Greater Bendigo towards a contemporary model community of sustainability and a regional centre in the State of Victoria, there is little effort being made in terms of a systematic evaluation of the capacity of the physical landscape in the Bendigo area. A literature survey reveals that so far no comprehensive urban development land suitability analysis has previously been undertaken for the whole of Greater Bendigo area other than some brief restrictive zone analyses presented in the literature (DPCD, 2010a, b; City of Greater Bendigo, 2015). While we inherit the legacy and excellence in urban planning, community development, and place making in Victoria and Australia, which could be possibly attributed to the legacy of Howard's 'Garden City' (Freestone and Hutchings, 1993; Hall, 2009) idea centuries ago, it is essential to bring new ideas, new technologies, new approaches for gathering and analysing data to support decision making in city and town planning practice. The emerging geodesign field is arguably the best evidence for this new trend in urban and landscape planning today (Steinitz, 2012; Bishop, 2013; You, 2013; Moura, 2015). Therefore, using a GIS-based weighted overlay analysis, this study aims to generate a complete land-use plan for urban growth covering the whole of Greater Bendigo area based on which guidance recommendation can be made to assist long-term urban development planning in Bendigo.

## METHODOLOGY AND DATA COLLECTION

The estimated increment of 45,572 persons by 2030 in Greater Bendigo (Forecast.id, 2015) has encouraged Planning Authorities to initiate a series of plans that help to determine an adequate provision of housing, services and infrastructure in the area. According to the Department of Transport, Planning, and Local Infrastructure 18,900 new dwellings are required in Bendigo to satisfy the upcoming population growth (Department of Transport, Planning and Local Infrastructure (DTPLI), 2015). In order to identify the most suitable areas to allocate this amount of dwelling units, social, economic and environmental factors should be considered. Bendigo has experienced a notable development during the past decades; education, health, commerce and professional services represent a significant contribution for the community as well as important sources of employment (City of Greater Bendigo, 2005). The presence of roads and rail facilities contributes to the connectivity between regional cities providing opportunities for growth in Victoria (DTPLI, 2014). Transport infrastructure, education and health, represent significant facilities and are used as

anchors for growth. Through complementing and enhancing what has been already built, the benefits from the investment that has been made in the past will increase. Moreover, it will locate people in proximity to one another, and influence the generation of jobs. Additionally, natural resources and geographical characteristics provide the city an extra value.

Of all spatial explicit modeling approaches, overlay mapping is easy to undertake and has been applied in land-use suitability analysis for urban development from before the GIS technology was invented and many landscape architects used transparent overlay by hand-drawn techniques (Steinitz et al., 1976). McHarg (1969) created enormously sophisticated overlay maps combining multiple thematic maps using hand-drawn overlay. McHarg's spatial overlay approach in parkway planning along with his other projects that were documented in his book *Design with Nature* (McHarg, 1969) has been quoted by researchers today as evidence of spatial thinking and foundations of the modern GIS technology (Steiner, 2013). Suitability analysis has been widely used in site selections (AbuSada and Thawaba, 2011; Perpiña et al., 2013; Jelokhani-Niaraki and Malczewski, 2015). Today highly complicated GIS applications across time and space are proposed to inform physical landscape and urban planning strategies (Miller, 1993; Steinitz, 2012; Chen and Lee, 2015) or broader urban issues relevant to suburbanization and urban planning management at city and regional scales (AbuSada and Thawaba, 2011). Most recently, the land-use suitability approach has been applied to highly densely populated Beijing to seek the most desired city planning and management strategies for best design outcomes (Liu et al., 2014).

The most common spatial models used in GIS-based suitability studies fall into two fundamental classes of multi-criteria evaluation (MCE): Boolean overlay or weighted overlay (Malczewski, 2004). In Boolean overlay models, each criterion is classified into two subsets delineating whether or not a particular area is suitable. Criterion maps are then layered using logical connectives (i.e. AND, OR). One primary shortcoming of Boolean analysis is that criteria can only be TRUE or FALSE, which creates discrete boundaries between variables. This imposes artificial precision on mapped results and fails to model more nuanced degrees of suitability. In contrast, models that use weighted overlay combine each criterion into categories; these categories are then weighted based on their importance as decided by professionals in the field, so when combined, one criterion with relative low suitability can be recompensed by the high score of another (Lewis et al., 2014). On one hand, the strengths of weighted overlay approach lie in the fact that it allows expert knowledge to play a role in the planning decision making so that the vision of City of Greater Bendigo is not lost during the process, considering the nature of the question (i.e. broader policy-level urban planning strategies) under investigation. Therefore in this study weighted overlay approach is used to assess the land-use suitability for urban growth in Bendigo. On the other hand, weighted overlay may introduce subjectivity to the decision-making process since the weight (%) is assigned arbitrarily to each set of criteria. In this study, a balance between the two is sought by using mainly key criteria that are relevant to each planning goal at the broader urban landscape scale. Other planning or design details are not included in the analysis in order to avoid weakening the reliability of the outcome from the analysis.

Five objectives are established as priorities for the selection of suitable areas as follows.

**1) A connected city:** The first planning goal is to consider the benefits and opportunities that the existing infrastructure offers to the city and the community. The first objective is focused on sustainable transport and connectivity between Bendigo and the regional cities and activity centers, encouraging growth along transport corridors.

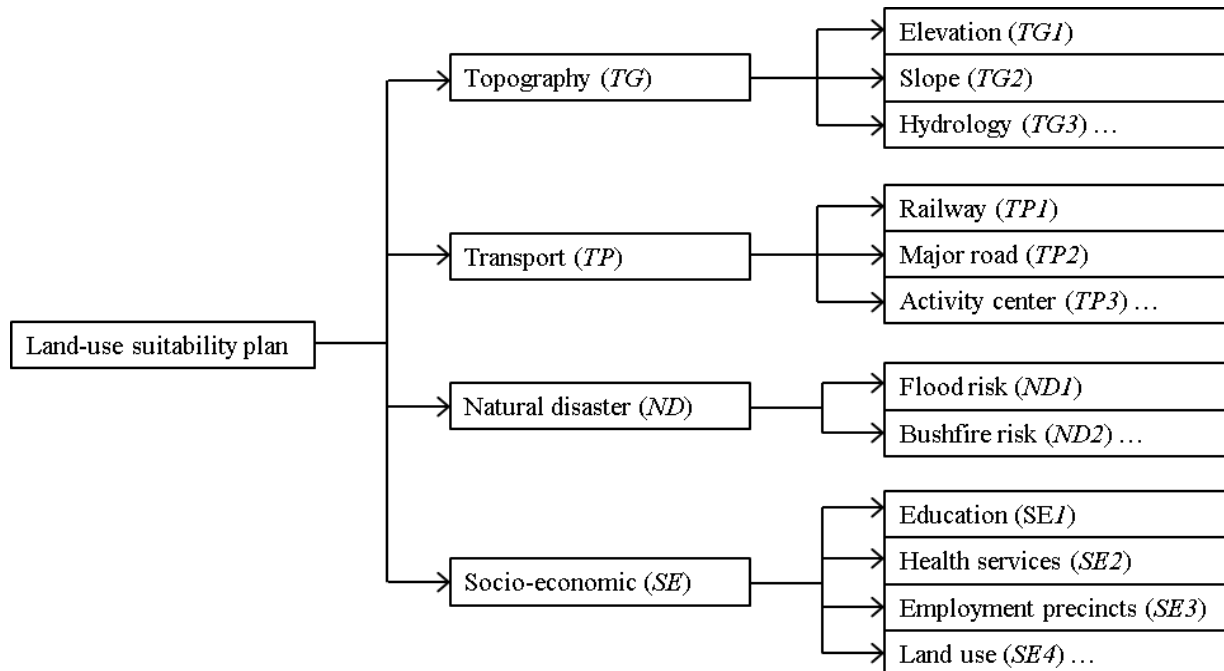


Figure 2. Geophysical and socio-economic factors considered in this study.

**2) A city of equality:** The second planning goal is to locate areas for future growth in proximity to education institutions and health services which are two basic requirements in every person's life. This goal is of particular significance for a city like Bendigo which has been renowned for its health care facilities and services.

**3) An ecological city:** This planning goal supports the protection of reserved forest and native vegetation acknowledging the importance for flora and fauna considering biodiversity is one of the most important visions for the sustainable growth of the city.

**4) A safe city:** This goal recognizes that the area can be affected by natural threats and disasters; therefore future developments should avoid certain areas which are vulnerable to flood and bushfire risks which are held as the two greatest dangerous risks for the city in the past couple of decades.

**5) A compact city:** The last goal emphasizes the importance of proximity between urban developments in order to take advantage of existing resources, infrastructure, and facilities in the urbanized city core of the city thus to reduce the total cost for housing development (and safeguard housing affordability) to accommodate increasing urban population in the city.

Data corresponding to each of the planning goals are collected, compiled, and integrated in a GIS using the methodological framework as follows (Figure 2). ESRI ArcGIS 10.2.2 is used for data analysis.

#### Input data

The planning language for each planning goal is translated into spatial/geographical/GIS language so that it can be put into the

GIS models for analysis. For example, for the Transport (TP) planning goal, the criterion 'Proximity to major roads' is translated to 'creation of a Euclidean distance raster layer based on the major road vector layer'. Therefore, for data collection concerns, the 'major road' dataset has to be identified and edited if necessary (in many occasions only a general 'road' layer is available, thus GIS-based process has to be taken (e.g. select by attribute, export data, etc.) to extract only the major roads from all roads feature in the dataset). Similarly, all required data are collected from reliable sources are collected to address each of the planning goals established in 3.1. The type, source, and usage under planning criteria of each dataset are given below (Table 1).

## RESULTS

### A connected city - Accessibility to existing infrastructure

A well-developed public transport network, structured roads, and a linked bike network are some aims established by Plan Melbourne which will improve the connectivity between regional cities (DPTLI, 2014). Bendigo is served by high capacity urban transport and roads and train facilities which represent an opportunity for growth and densification and act as attractors of investment; whereas the presences of roads increment the possibilities of public transport provision. The Euclidean distance analysis indicates the areas located in proximity to roads infrastructure and train stations are also better connected with key regional cities in Victoria

**Table 1.** Input data for the land-use suitability analysis.

Layers	Criteria	Layers	Data source
<i>Connected City</i>	Proximity to train stations	Train station point feature class	Vicmap (land.vic.gov.au)
	Proximity to major roads	Major road	Vicmap
<i>City of Equality</i>	Proximity to health services	Hospital, health service, and aged care shape files	Vicmap; ABS (Australia Bureau of Statistics)
	Proximity to educational institutions	Primary, secondary and tertiary institutions	Vicmap; ABS
<i>Ecological City</i>	To protect environmental and landscape significant areas	Environmental Significance Overlay (ESO), Significant Landscape Overlay (SLO) and Vegetation Protection Overlay (VPO)	Victorian Government Data Directory (data.vic.gov.au)
<i>Safe City</i>	To avoid LSIO, watercourse and water area buffers, bushfire prone areas	Land Subject to Inundation Overlay (LSIO), Bushfire Management Overlay (BMO)	Victorian Government Data Directory; Vicmap; Geoscience Australia
<i>Compact City</i>	Proximity to established neighborhoods	Built-up land	Geoscience Australia

thus have higher development potential (Figure 3). The reclassification determines potential areas of growth along transit corridors as well as the zones that can be served by an efficient road and public transport network.

#### **A city of equality - Accessibility to education and health services and jobs**

Future development is considered to be located in proximity to education and health precincts which additionally represent a significant source of employment within Bendigo. St. John of God, Bendigo Base Public Hospital, Regional Institute of TAFE, La Trobe University and Bendigo Senior Secondary College are part of the infrastructure that supports the presence of professional and skilled labor contributing to the enhancement of the area (Figure 3). Education and health facilities represent an important source of employment and services within Bendigo. The reclassification of Euclidean distance indicates the areas that are benefited from the mentioned amenities. On the other hand these districts are considered core development areas (City of Greater Bendigo, 2012), reinforcing the accommodation of diverse housing types and mixed use developments.

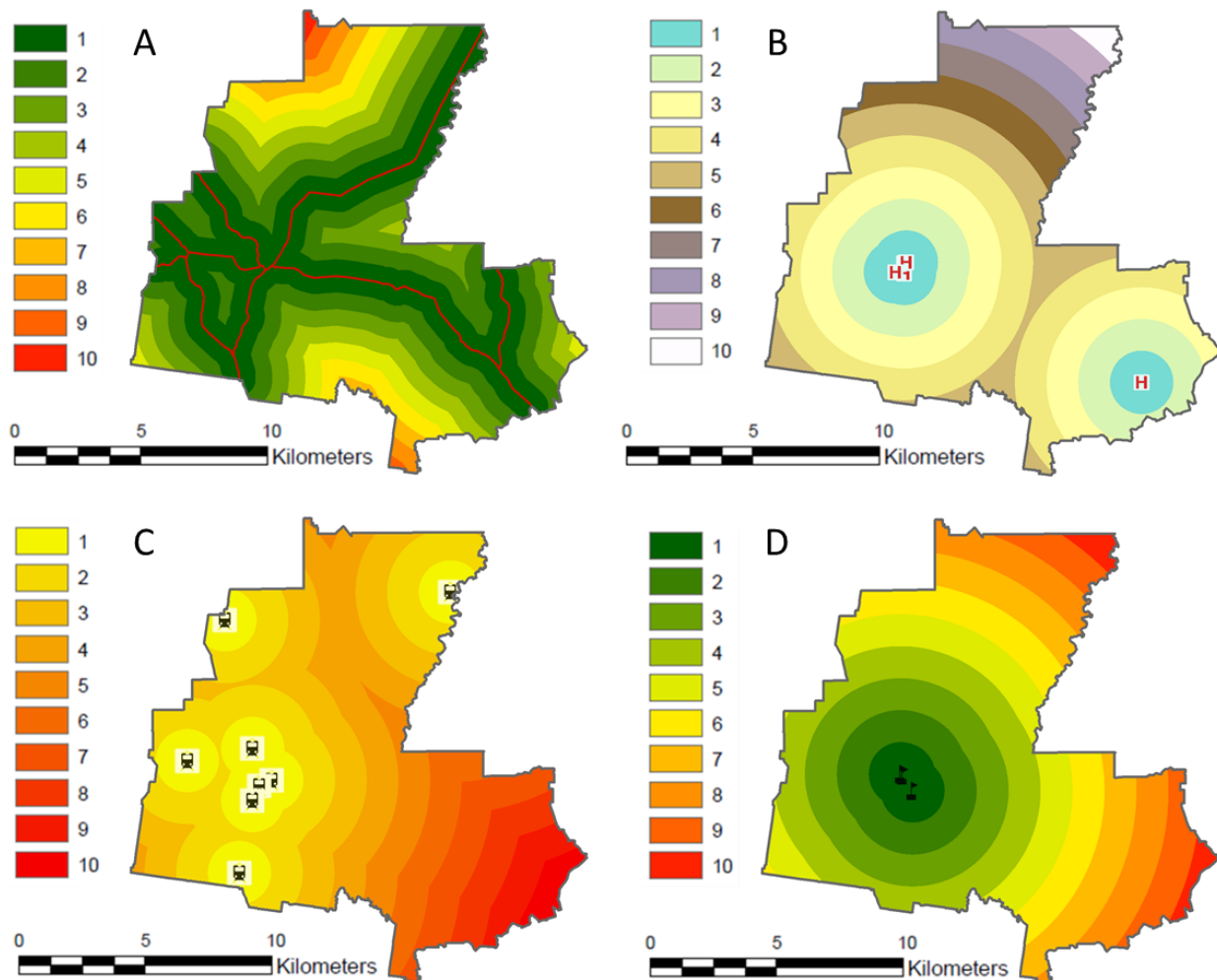
#### **An ecological city - Conservation of ecosystem and natural resources**

The uniqueness of Greater Bendigo can be its complex urban system integrating with 'green' ecosystems' (City of Greater Bendigo, 2014). This requires more strategic, innovative, and forward-looking approaches to create a livable, resilient, ecological and sustainable city with retaining its valuable ecology and unique culture. The

surrounding linear and continuous natural systems (Environmental Significance Overlay: ESO) are key reasons that people choose to live in Bendigo and tourists choose to travel there (City of Greater Bendigo, 2014). Forests represent a valuable natural resource within Bendigo which accommodates a wide range of recreational activities that benefit locals and visitors. During the last years initiatives such as "City in the Forest" have been implemented involving different stakeholders and the community in order to protect the forest and natural areas (City of Greater Bendigo, 2005). The present objective aims to protect and conserve the ecosystem and natural resources. Consequently, future developments must not be located in the conserved areas (Figure 4).

#### **A compact city - Proximity to established neighbourhoods**

Due to abundant land available and a relatively small population in Australia, many Australian cities, especially regional cities, are suffered from the adverse effect from urban sprawl such as increased traffic and demand for mobility and increased investment on infrastructure (Ewing et al., 2002; Cameron et al., 2004; Kahn, 2000), traffic congestion, landscape fragmentation and loss of biodiversity (Alberti, 2005), reduced landscape attractiveness and attachment to places (Sullivan and Lovell, 2006) and alterations of the hydrological cycle and flooding regimes (Bronstert et al., 2002; Carlson, 2004; McCuen, 2003). Bendigo's urban area offers a wide range of services and activities including retail, education health, and business. Future growth areas will be located in proximity to consolidated urban zones (Figure 5) in order to increment the



**Figure 3.** The Euclidean distance to major roads (A), health services (B), train stations (C), and education (D) is reclassified into 10 classes; class code 1 means highest development potential and 10 lowest development potential.

provision of accessible facilities and employment, and reduce the negative impact from urban sprawl.

### The weighted overlay

Based on all reclassified input layers, a weighted overlay analysis was conducted in ESRI ArcGIS package (version 10.2). In weighted overlay, the preferred criteria are processed and input with different weighting (%) applied to each criterion (Table 2). The weighting is drawn from the Greater Bendigo Residential Strategy (City of Greater Bendigo, 2015) and its emphasis on “Complete Neighbourhoods” and “integrating sustainable transport with changing land-use patterns”. However safety issues are of utmost importance thus the *Safe City* goal is given primary weighting (20%) in the analysis (Table 2), with *Compact*

*City* and *City of Equality* given secondary weighting (15%); and the weight for remainder is 10%. After the application of the Weighted Overlay, several levels of suitability for future growth were identified in greater Bendigo. The obtained land-use suitability map is reclassified using the suitability value (code = 10 as “primary suitability”) and levels 0 to 9 as “secondary or restricted”. The result of the weighted overlay analysis is presented in Figure 6.

As urban population growth projections indicates that the current levels of dwelling construction activity in Bendigo are insufficient to meet potential demand, and these demand projections are 29% greater than recent building approval activity. Under this scenario, the total (excluding existing vacant residential lots) new dwelling units expected to be supplied by 2030 is 18,500 residential lots (Department of Planning and Community Development, 2010b). Under the conventional

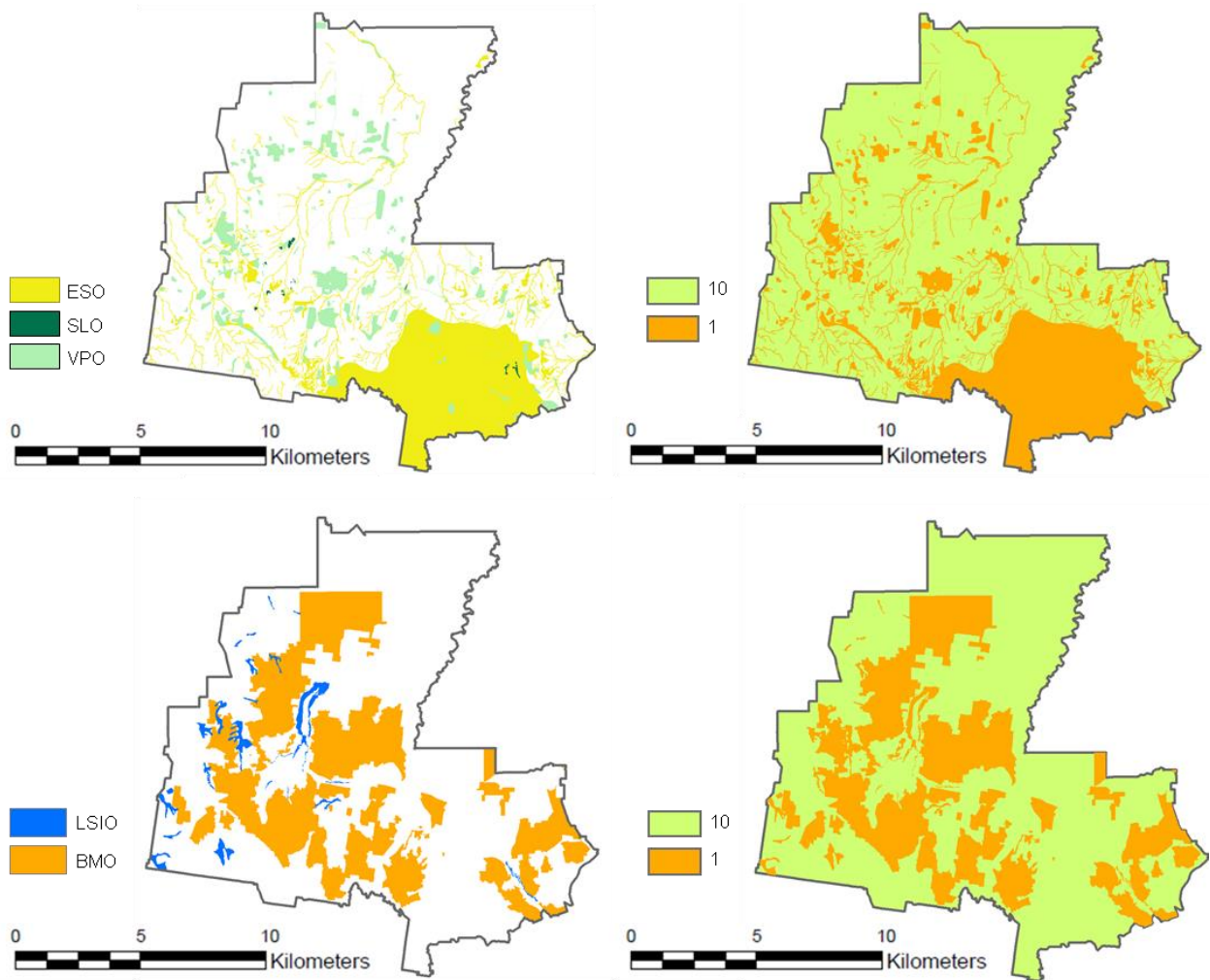


Figure 4. Reclassification of reserved land (top) and flood- and bushfire-prone areas (bottom) which are restricted for development (Class code 1 means restricted and 10 suitable).

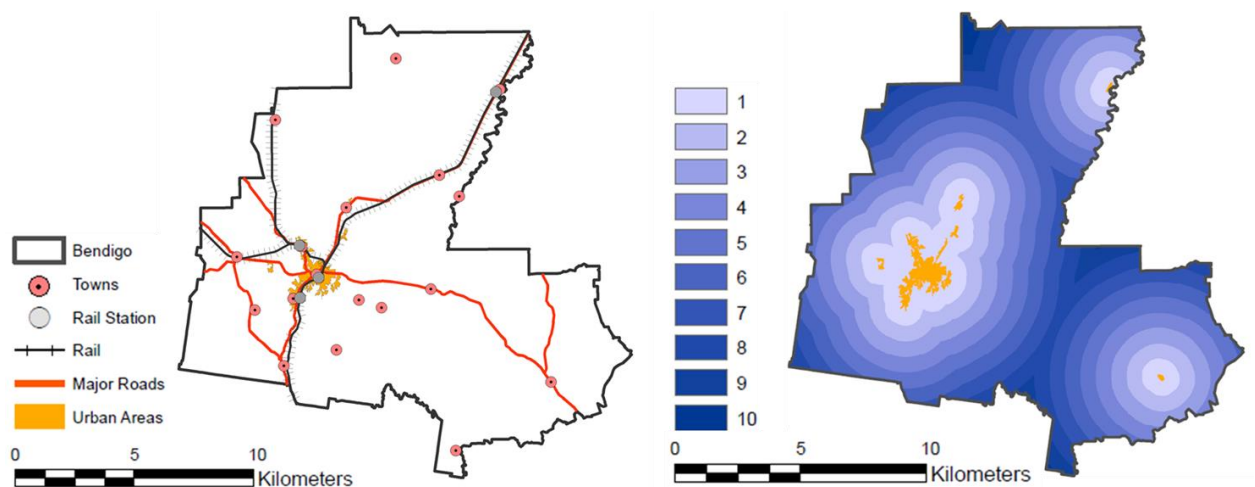
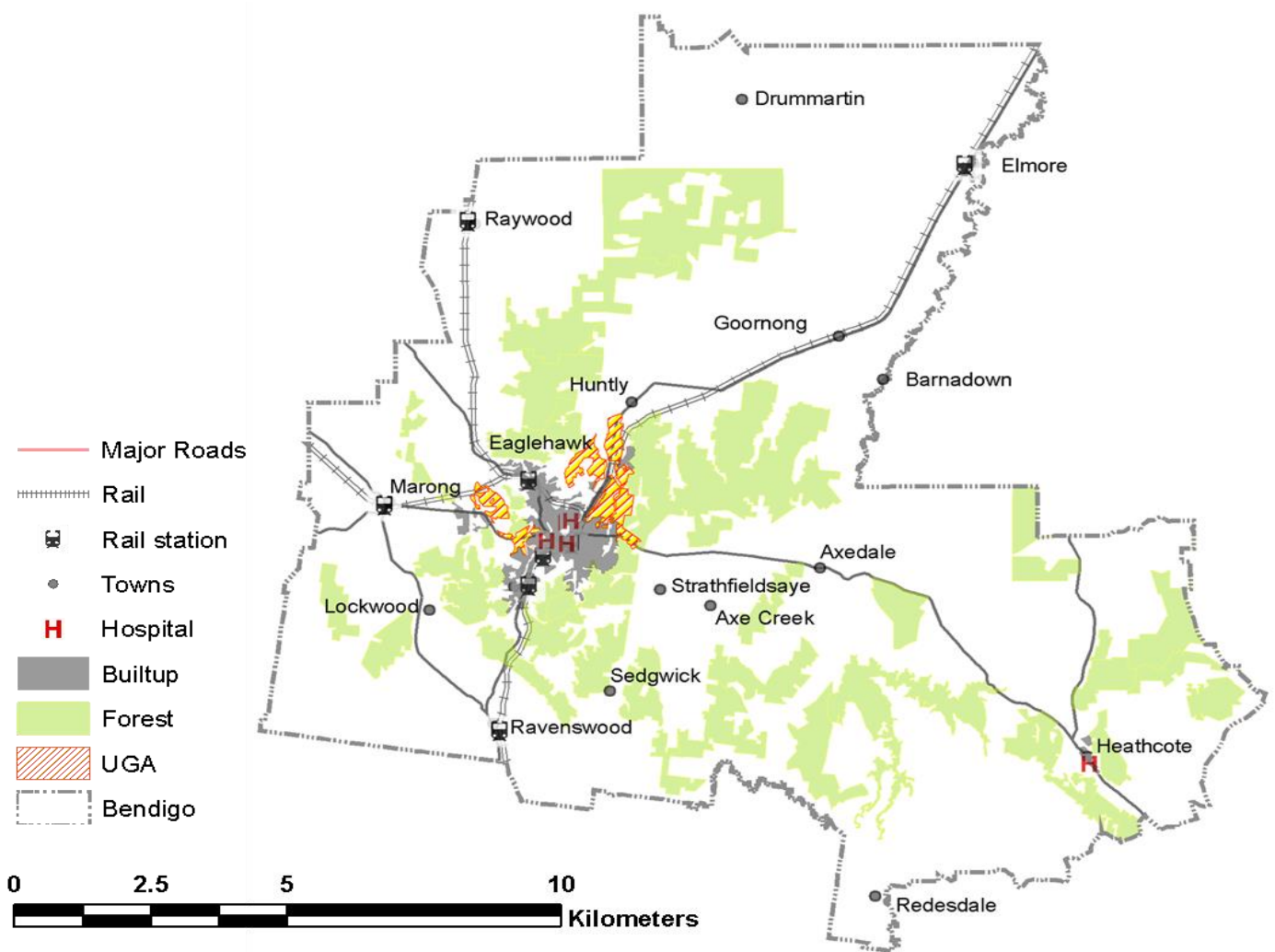


Figure 5. The Euclidean distance to established urban areas is reclassified into 10 classes; class code 1 means highest development potential and 10 lowest development potential.



**Table 2.** Contribution (%) of different input layers in the weighted overlay analysis.

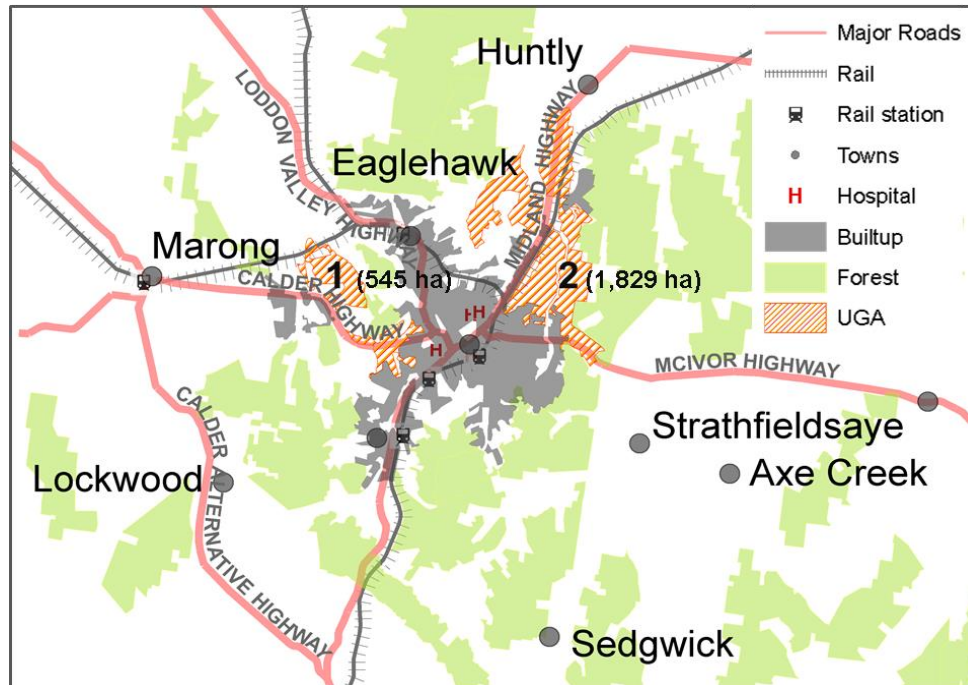
Planning Criteria and Goals	Raster Layers	Influence (%) in Overlay
<i>Connected City</i>	Proximity to train stations	10
	Proximity to major roads	10
<i>City of Equality</i>	Proximity to health services	15
	Proximity to educational institutions	15
<i>Ecological City</i>	ESO, SLO, VPO	15
<i>Safe City</i>	LSIO, BMO , watercourse and water area buffers	20
<i>Compact City</i>	Proximity to established neighbourhoods	15



**Figure 6.** Two areas suitable for urban development are identified using the land-use analysis based on weighted overlay for Bendigo.

development density (1 ha = 10 dwelling units), adequate land that satisfy the requirements to accommodate 18,500 dwelling units would be 1,850 ha. In GIS, the

weighted overlay raster layer is converted to polygon and the resultant vector layer allows calculating the geometry (in hectares) of the potential sites. As the suitable land is



**Figure 7.** The identified suitable Urban Growth Areas (UGAs) for Bendigo.

larger than required, this analysis could be used to create a longer term urban growth plan which is discussed below.

Through the Bendigo case the following strengths of the GIS-based land use suitability analysis has been demonstrated: 1) The suitability analysis makes urban planning decision-making more rational, thus the planning outcome is can be easily communicated, understood, and accepted by the public, which means less resistance in the implementation process; 2) the overlay analysis includes data from multiple sources and aspects including geographical, social, economic, etc., and 3) the weighted overlay allows manipulation of the overlay process by assigning different weights for different input layers, so that the factors playing a more important role will have larger influence in shaping the result of the overlay analysis. This is the uniqueness of weighted overlay compared with other overlay methods such as binary overlay, fuzzy overlay, or ranking overlay. However there are also weaknesses when using weighted overlay. One of the critical issues is the defined scales applied to the input data (normally 1 to 9; 1 to 10 used in this study) and it assumes that more favorable factors result in the higher values in the output raster, therefore identifying these locations as being the best. The discrete nature of this transformation of data may compromise the information of continuous nature in the original dataset. The data preparation and analysis processes are also time-consuming and computing-intensive.

## DISCUSSION

### Planning for urban sustainability in longer terms

A comprehensive assessment of land-use suitability for urban growth in City of Greater Bendigo is carried out in this study. The selected areas are located in areas not prone to natural disasters and in proximity to established neighbourhoods, jobs, education and health services, and major roads and train facilities. Current plans such as Greater Bendigo Planning Scheme (DTPLI, 2014) and the Bendigo Residential Development Strategy (City of Greater Bendigo, 2015) have considered the presence of transport infrastructure for future growth within these areas. For instance, improvement of rail services to Eaglehawk is a confirmed requirement that will contribute to enhance the connections between regional cities in Victoria (DTPLI, 2014).

As urban growth planning are to make plans to accommodate predicted future changes (housing for predicted urban population increase by 2030 in this study), it may be useful to plan for the far future. The final result covers 2,424 ha divided in two different sites of land (Figure 7). The first site, composed by three areas along the Midland Highway is close to Huntly and Eaglehawk (total land 1,829 ha). This site is coincidentally considered an area of new development (DTPLI, 2015) by the local government and it is located within the urban growth boundary. The second site is

located in proximity to Eaglehawk and covers 545 ha land. As the first site is almost big enough for the 2030 urban growth targets thus the 2<sup>nd</sup> site could be used for longer term growth plan such as Bendigo 2050 or 2060. Both sites can be attributed to the *Compact City* and *Connected City* goals.

### GIS-based land-use suitability analysis to support urban planning decision making

GIS is a crucial tool used by this study to gain an understanding of the existing spatial composition of the City of Greater Bendigo. In this regard, the maps generated as part of this study, not only provide a visual representation of the Municipality's existing features, but also provide additional knowledge regarding the way in which these features interact, thereby influencing the City's future urban growth prospects. The generation of such additional knowledge is an invaluable characteristic of GIS, exploited by all levels of government in Victoria to effectively manage the State's existing assets, as well as to prepare future planning initiatives at the State, regional, and local levels. The study demonstrates that the application of spatial overlay is efficient in land-use suitability analysis for urban development.

As a final note, although this study's focus is the identification of land on a municipal-wide scale, this represents only the first stage of the strategic planning process. In order that the identified areas of land can successfully contribute to Greater Bendigo's sustainability attainment goal, it is important that the key principles of the "Compact City" model also resonate into the detailed urban design phase of the planning process. In this regard, GIS will continue to play an important role in the creation of communities that contribute to the City's overarching sustainability and livability objectives – particularly in relation to their walkability (including the provision of connecting footpaths), diversity (including the provision of varying lot sizes and affordable housing options), resilience (ensuring the appropriate development and ongoing management of flood prone areas), and accessibility (including the provision of local services and facilities to complement those already provided within nearby towns).

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### Conflict of Interests

The author has not declared any conflict of interests.

### REFERENCES

- AbuSada J, Thawaba S (2011). Multi criteria analysis for locating sustainable suburban centers: A case study from Ramallah Governorate, Palestine. *Cities* 28(5):381-393.
- Alberti M (2005). The effects of urban patterns on ecosystem function. *Int. Reg. Sci. Rev.* 28(2):168-192.
- Angelis-Dimakis A, Biberacher M, Dominguez J, Fiorese G (2011). Methods and tools to evaluate the availability of renewable energy sources. *Renew. Sust. Energ. Rev.* 15:1182-1200.
- Bishop I (2013). Optimization in deodesign. *Landsc. Archit. Frontiers* 1(6):64-75.
- Bronstert A, Niehoff D, Bürger G (2002). Effects of climate and land-use change on storm runoff generation: Present knowledge and modelling capabilities. *Hydrol. Process.* 16:509-529.
- Cameron I, Lyons TJ, Kenworthy JR (2004). Trends in vehicle kilometres of travel in world cities, 1960–1990: Underlying drivers and policy responses. *Transp. Pol.* 11:287-298.
- Carlson TN (2004). Analysis and prediction of surface runoff in an urbanizing watershed using satellite imagery. *J. Am. Water Resour. Assoc.* 40(4):1087-1098.
- Carthew S, Allan M (2005). Strategic Planning in Regional Cities - New Conceptions. State of Australian Cities, pp. 1-12.
- Chen S, Lee V (2015). From metropolis to allotment: Scaled system thinking in advancing landscape studio knowledge. In: Buhmann E et al. (eds, 2015) *Systems Thinking in Landscape Planning and Design: Landscape Architecture 3.0*. Herbert Wichmann Verlag pp. 344-353.
- Childers DL, Pickett STA, Grove JM, Ogden L, Whitmer A (2014). Advancing urban sustainability theory and action: Challenges and opportunities. *Landsc. Urban Plan.* 125:320-328.
- City of Greater Bendigo (2005). Bendigo CBD Plan. Available at [https://www.bendigo.vic.gov.au/files/48f53bf9-b932-4470-ab6da0d700ef31ff/bendigo\\_cbd\\_plan\\_executive\\_summary\\_and\\_introduction.pdf](https://www.bendigo.vic.gov.au/files/48f53bf9-b932-4470-ab6da0d700ef31ff/bendigo_cbd_plan_executive_summary_and_introduction.pdf). (Accessed 11 June, 2015).
- City of Greater Bendigo (2014). Municipal Strategic Statement. Available at [http://planningschemes.dpcd.vic.gov.au/schemes/greaterbendigo/ordnance/21\\_mss05\\_gben.pdf](http://planningschemes.dpcd.vic.gov.au/schemes/greaterbendigo/ordnance/21_mss05_gben.pdf) (Accessed 18 June 2015).
- City of Greater Bendigo (2015). Greater Bendigo Residential Strategy. Available at [https://www.bendigo.vic.gov.au/Services/Planning/Strategic\\_Planning/Current\\_Projects/Greater\\_Bendigo\\_Residential\\_Strategy](https://www.bendigo.vic.gov.au/Services/Planning/Strategic_Planning/Current_Projects/Greater_Bendigo_Residential_Strategy) (Accessed 9 July, 2015).
- Department of Planning and Community Development (DPCD) (2010a). Regional Residential Report - Greater Bendigo.
- Department of Transport, Planning and Local Infrastructure (DTPLI). (2014). Plan Melbourne. Available at <http://www.planmelbourne.vic.gov.au/Plan-Melbourne> (Accessed 30 July, 2015).
- Department of Planning and Community Development (DPCD) (2010b). Victoria's regional centres – A generation of change.
- DTPLI (2015). Greater Bendigo Planning Scheme. Planning Schemes Online <http://planningschemes.dpcd.vic.gov.au/schemes/greaterbendigo> (Accessed June 28, 2015).
- Ewing R, Pendall R, Chen D (2002). *Measuring Sprawl and its Impact*. Smart Growth America, Washington DC.
- Forecast.id. Population forecasts (2015). <http://forecast.id.com.au/bendigo/home> (Accessed 7 July, 2015).
- Freestone R, Hutchings A (1993). Planning history in Australia: The state of the art. *Plann. Perspect.* 8(1):72-91.
- Girvetz EH, Thorne JH, Bery AM, Jaeger JA (2008). Integration of landscape fragmentation analysis into regional planning: A statewide multi-scale case study from California, USA. *Landsc. Urban Plann.* 86(3):205-218.
- Graymore ML, Wallis MAM, Richards AJ (2009). An Index of Regional Sustainability: A GIS-based multiple criteria analysis decision support system for progressing sustainability. *Ecol. Complex* 6(4):453-462.
- Hall P (2009). Looking Backward, Looking Forward: The City Region of the Mid-21st Century. *Reg. Stud.* 43(6):803-817.

- Jelokhani-Niaraki M, Malczewski J (2015). Decision complexity and consensus in Web-based spatial decision making: A case study of site selection problem using GIS and multicriteria analysis. *Cities* 45:60-70.
- Joerin F, Theriault M, Musy A (2001). Using GIS and outranking multicriteria analysis for land-use suitability assessment. *Int. J. Geogr. Inf. Sci.* 15:153-174.
- Lewis SM, Gitts G, Kelly M, Dale L (2014). A fuzzy logic-based spatial suitability model for drought-tolerant switch grass in the United States. *Comput. Electron. Agr.* 103:39-47.
- Liu R, Zhang K, Zhang Z, Borthwick AGL (2014). Land-use suitability analysis for urban development in Beijing. *J. Environ. Manage.* 145:170-179.
- Malczewski J (2004). GIS-based land-use suitability analysis: a critical overview. *Progress Plann.* 62:3-65.
- Malczewski J (2006). Ordered Weighted Averaging with fuzzy quantifiers: GIS-based multi-criteria evaluation for land-use suitability analysis. *Int. J. Appl. Earth Obs. Geoinfo.* 8:270-277.
- Marull J, Pino J, Mallarach JM, Cordobilla MJ (2007). A land suitability index for strategic environmental assessment in metropolitan areas. *Landscape Urban Plann.* 81:200-212.
- McCuen RH (2003). Smart growth: Hydrologic perspective. *J. Prof. Eng. Ed. Pr.* 129(3):151-154.
- McHarg IL (1969). *Design with Nature*. Garden City, New York, Natural History Press.
- Miller L (1993). Charles Eliot, Preservationist, Park Planner, and Landscape Architect. Department of Landscape Architecture, State College, Pennsylvania State University, Pennsylvania.
- Moura ACM (2015). Geodesign in Parametric Modeling of urban landscape. *Cartogr. Geogr. Inform. Sci.* 42(4):323-332.
- Perpiña C, Martínez-Llario JC, Pérez-Navarro A (2013). Multicriteria assessment in GIS environments for siting biomass plants. *Land Use Pol.* 31:326-335.
- Ramachandra TV, Shruthi BV (2007). Spatial mapping of renewable energy potential. *Renew. Sust. Energ. Rev.* 11:1460-1480.
- Rojas C, Pino J, Jaque E (2013). Strategic environmental assessment in Latin America: A methodological proposal for urban planning in the Metropolitan Area of Concepción (Chile). *Land Use Pol.* 30(1):519-527.
- Steiner F (2013). Representing Complexity. *Landscape Archit. Frontiers* 1(6):44-63.
- Steiner F, McSherry L, Cohen J (2000). Land suitability analysis for the upper Gila River watershed. *Landscape Urban Plan.* 50:199-214.
- Steinitz C (2012). *A framework for geodesign: Changing geography by design*. Redlands, CA, ESRI Press.
- Steinitz C, Parker P, Jordan L (1976). Hand-drawn overlays: Their history and prospective uses. *Landscape Archit.* 66(5):444-455.
- Sullivan WC, Lovell ST (2006). Improving the visual quality of commercial development at the rural-urban fringe. *Landscape Urban Plan.* 77:152-166.
- Trading Economics (2014). Urban population growth (annual %) in Australia. Available at <http://www.tradingeconomics.com/australia/urban-population-growth-annual-percent-wb-data.html> (Accessed 1 December 2015).
- You H (2013). Practice of Geodesign Approach in Macro-scale Land Use Planning: Scenario-based Simulation and Evaluation of Land Use Change in Beijing. *Landscape Archit. Frontiers* 1(6):122-131.

A hand in a suit sleeve holds a pen over a world map. The map is overlaid with a glowing green network of lines and nodes, symbolizing global connectivity and regional planning. The background is a light-colored wooden plank wall.

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