Stormwater management impacts of small urbanising towns: The necessity of investigating the ‘devil in the detail’

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HIGHLIGHTS

- Investigating the nuances of urbanisation impact on urban hydrology in a small town
- Analyses of population, land use/cover changes and hydrological impact in 10 years
- Growth patterns present in existing (subtle) & new developed areas (significant)
- Slight increases in imperviousness, likely significant cumulative impact of minor storms
- Fine-scale analysis a necessity to support adaptive future planning of small towns

GRAPHICAL ABSTRACT

ABSTRACT

In many parts of the world, small towns are experiencing high levels of population growth and development. However, there is little understanding of how urban growth in these regional towns will impact urban runoff. We used the case study of Wangaratta, located in South-East Australia, between 2006 and 2016, to investigate land cover changes and their impacts on urban runoff discharge. Detailed spatio-temporal analysis (including neighbourhood composition analysis and supervised classification of aerial imagery) identified that population, land use and land cover changes in Wangaratta, although subtle, were mostly driven by residential growth in the outskirts of the town, where there were large increases in impervious surface area. Overall, the urban growth was minimal. However, in spite of these small changes, a sub-catchment only SWMM model showed that the increase in impervious surface area nevertheless resulted in a statistically significant increase in total runoff across the town. Particularly, this increase was most pronounced for frequent and shorter storms. The analysis of urban development pattern changes coupled with urban hydrological modelling indicated that land cover changes in regional towns, especially when analysed in detail, may result in hydrological changes in the urban region (likely to be exacerbated in coming years by changing climate) and that adaptation efforts will need to adopt a variety of approaches in both existing and growth zones. Our findings highlight the necessity of detailed fine-scale analyses in small towns as even subtle changes will have substantial future implications and robust planning and adaptation decisions are even more important when compared to larger cities due to
1. Introduction

In recent decades, small, regional towns (i.e. small urban settlements or secondary towns – Mitka and Tilley (2020)) in many parts of the world have experienced increasing population growth and land use change (Jansen et al., 2012; Shackleton et al., 2018; Beer and Clover, 2009; Gros-Balthazard and Talandier, 2020) and are predicted to double in size over the next 15 years (Pilgrim et al., 2007). In Australia, over 400,000 people relocated from capital cities to regional areas between 2011 and 2016 (Regional Australia Institute, 2019). This represents over 63% of all relocations in this time period. This population increase in regional areas in Australia has largely been driven by government policies designed to decrease the urban population. For example, in the state of Victoria in south-east Australia, incentives (e.g., skilled migration grants, first home buyer grants and fringe tax benefits) have been provided to individuals and businesses relocating to regional areas (Coleman, 2019). Relocations have also been driven by specific policies and funding schemes (e.g., ‘Build Better Regions Fund’, Regional Growth Fund and Jobs and Investments packages) designed to support regional communities and incentivise migration from urban to regional areas (Australian Government, 2020).

The population in regional towns is expected to continue its upwards trend in the coming decades in some areas in countries such as Australia (Jansen et al., 2012), India (Jain and Korzhenevych, 2019; Chakraborti et al., 2018) and China (Qian and Xue, 2017) due to their perceived better social infrastructure (e.g., schools, hospitals) (Jain and Korzhenevych, 2019), high economic growth in regional areas (Jain and Korzhenevych, 2019), and both community and government rural renewal programs (Toerien, 2018; Qian and Xue, 2017; van Staden and Haslam McKenzie, 2019). As such, there is a critical need to ensure that the infrastructure in these towns can manage recent and future population growth and land use change. In particular, for the safety and general wellbeing of its residents, there is a need to ensure that the drainage system has the capacity to cope with potential changes in urban hydrology as a result of increased development. In addition, it is important that urbanisation impacts on natural waterways (Walsh et al., 2012), which not only support local ecosystems but also provide significant liveability benefits (Dunn et al., 2017), are minimised. As such, sustainable and resilient development of towns is vital, particularly within the context of managing land use change and accommodating the growing population.

Previous studies have quantified the relationship between land cover change and urban hydrology. However, these have focussed on the impact of land use change in high-density areas in major cities (Huang and Pathirana, 2013; Nirupama and Simonovic, 2006; Pauleit and Duhme, 2000). There is still a lack of understanding if and how the urban hydrology in less densely developed regional towns will be affected by land cover change, and the relationship between land cover change and population growth and land use change. Findings from studies on high-density urban regions cannot necessarily be extrapolated to regional centres (Mitka and Tilley, 2020) because of differing population densities and spatial patterns in land use and land cover (Humphreys et al., 2018). Therefore, more studies are required specifically focusing on regional areas. Existing methodologies applied to high-density urban areas are, however, transferable, e.g. analysis of high-resolution satellite imagery (Hussein et al., 2020), aerial imagery (Huang et al., 2017) and/or cadastres (Pauleit and Duhme, 2000) for identifying land use and land cover change. For example, satellite imagery with a resolution of 30 m by 30 m was used in a study of Kolkata (India) to identify the change in urban hydrology land use-land cover change between 1980 and 2014 (Mukherjee et al., 2018). By learning from these previous studies, we can apply similar methods to regional areas.

It is critical to identify how population and land use change can affect land cover change, and impact of this land cover change on urban hydrology, if planners are to devise sustainable future plans for a town’s development. As urban development encompasses both expansion towards and beyond the urban fringe as well as infill development (e.g. the redevelopment of single dwellings into multi-level apartments and the densification of areas from single to mixed land uses), we need to understand how and to what extent these changes alter the spatial patterns of land use clustering and impervious surface covers. For regional towns, in particular, which share significant symbiotic relationships with its surrounding hinterlands (Courtney et al., 2007; Hinderink and Titus, 2002) this dynamic is likely to be more subtle compared to major cities, which encroach ‘mercilessly’ on the surrounding environment. Overall, we hypothesise that whilst urbanisation impacts of regional towns may be subtle, their nuances, i.e. ‘devil will lie in the detail’ of the urban matrix, are crucial to understand if sustainable and adaptive urban growth plans are to be developed. Change in urban hydrology resulting from land cover change have implications for water quality (Fletcher et al., 2014) and geomorphology of nearby waterways (Viertz et al., 2016), as well as the flood risk (Brown et al., 2009) within regional towns. As such, it is crucial to robustly assess the impact of urban growth on urban hydrology within regional towns.

This paper aims to develop a deeper understanding of the dynamics of small town urbanisation and population growth and understand the nuances of impacts that these impart on the urban hydrology. Based on a regional town in Australia undergoing rapid growth with a history of urban flooding, we leverage the availability and temporal consistency of high-resolution data sets to conduct a ‘deep-dive’ analysis of its development over a decade of growth (i.e. 2006 to 2016). The objectives of the study are twofold: (1) understand, at both regional and local scales, significant changes in spatial patterns due to urbanisation (from a population, land use and land cover perspective and in the context of the town’s future growth trajectories) and (2) quantify and benchmark the likely hydrologic impacts urbanisation has had on the urban drainage system. Our analytical and modelling approach in this investigation is transferable to other regional towns worldwide to help local governments implement appropriate management strategies to ensure that their towns are sufficiently prepared for future population growth and development.

2. Materials & methods

2.1. Case study description

We selected the Rural City of Wangaratta (referred to henceforth as Wangaratta), located in south-east Australia as our case study. Wangaratta is located approximately 250 km north-east of Melbourne at the confluence of two major rivers: the King and Ovens Rivers (Fig. 1). The town itself has an area of 57 km² and a population of 29,087 (ABS, 2018) correlating strongly with its industrial growth (Victorian Places, 2015). Wangaratta is a significant economic hub in the region, with economic output estimated at approximately AUD$3 billion (RCoW, 2020). The area was settled by the Pangerang People prior to European settlement in 1838. The town developed through the Gold Rush (1850s) before becoming an industrial hub (in the early
20th century) with manufacturing of Yakka and IBM products (Victorian Places, 2015).

Wangaratta was selected as the case study for this investigation because it has been experiencing a high growth rate (RCoW, 2020) with further increase in population growth expected. In 2016, Wangaratta’s population was projected to increase from 27,040 to 27,804 by 2031 (Victorian Government, 2016). However, this increase has been more rapid than initially expected as it already reached 29,187 by June 30, 2019 (.idcommunity, 2019a). Policies have been enacted within the town to accommodate the projected population growth. In particular, two major growth regions (subdivided into five key growth zones) were designated in the North-West and South (see Fig. 1a), which will provide housing for 7000 people (RCoW, 2018a; RCoW, 2018b). To ensure that we adequately incorporated these growth regions in our analysis and some additional hinterland areas, we used a case study boundary of 333 km², which included some of the rural land surrounding the town. In addition to higher growth than expected, Wangaratta is a regional town surrounded by rivers (Fig. 1). The impact of the town development on urban hydrology will have subsequent effects on the hydrology, water quality and geomorphology of nearby rivers (Fletcher et al., 2014; Vietz et al., 2016). Furthermore, Wangaratta also has a history of fluvial flooding, most severely in 1993 (SES, 2018). The severity of flooding is commonly measured by “where is it up to on Yogi?” (Morgan, 2015), who is the local unofficial flood marker shown in (Fig. 1b-left), located at Apex Park in the heart of the Wangaratta’s urban area. A recent study has indicated that flood extents are encroaching on urban areas (Water Technology, n.d.).

In this study, we focus on the time period of 2006–2016 for several reasons. On the one hand, the town population experienced a significant growth of 7% during this 10-year period (.idcommunity, 2019b) whereas on the other, these years align with the Australian census, available land use data and obtainable high-resolution aerial imagery in 2007 and 2017, explained hereafter.

2.2. Data collation and pre-processing

Table 1 summarises the different spatial data sets, which were collected for Wangaratta. With the exception of boundaries and natural features, which were used for data clipping and providing context for the analysis, and the elevation data, which was used in the modelling study, all other data sets were collected for the years 2006/2007 and 2016/2017. Time-dependent geographic layers include: (a) population counts from 2006 and 2016 from the Australian Bureau of Statistics, (b) land use classification for 2006 and 2016 (based on the Victorian Land Use Information System – VLUIS – Morse-McNabb et al. (2015)), and (c) high-resolution aerial imagery (dated 2007 and 2017) from the local council. The datasets used in this study are publicly available and quality controlled by local, state and federal government agencies.

All layers were clipped to the study boundary shown in Fig. 1a. We assumed that the 1-year offset between land use and land cover data (i.e. aerial imagery) due to the lack of available satellite imagery would have minimal impact on our analysis as the temporal difference of 10 years was still maintained. Population counts were converted to gross density by dividing the total population within a single census...
Table 1
Summary of data sets used in this study, their source, spatio-temporal information, description and analyses performed.

| Dataset                        | Date(s)    | Source | Format        | Description                                                                 | Analyses                                                                 |
|-------------------------------|------------|--------|---------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Aerial imagery                | 2007 & 2017| Wangaratta Council | Raster | Pixel resolution of 50 cm (2007) and 20 cm (2017) with imagery covering the case study area. Census and geopolitical districts for Victoria and Wangaratta Council | Impervious area analysis, setup of urban drainage model Clipping of spatial extents |
| Boundary                      | 2016       | Australian Bureau of Statistics | Vector (polygon) | Population and dwelling counts for both Australian census 2006 and 2016 at the finest spatial district level | Urban growth analysis                                                   |
| Demographics                  | 2006 & 2016| Australian Bureau of Statistics | Vector (polygon) | Map of case study region with land use information for respective years. | Land use change and spatial pattern analysis, setup of urban drainage model |
| Elevation (contours)          | 2018       | Wangaratta Council | Vector (line) | Contours with 50 cm height increments to create DEM for the case study region. | Setup of urban drainage model                                           |
| Land use                       | 2006 & 2016| VLUS (Morse-McNabb et al., 2015) | Vector (polygon) | Rivers flowing through Wangaratta                                           | Context-setting, locating confluenes                                    |
| Natural waterways              | 2020       | VIC Open Data repository (DELWP, 2014) | Vector (line) |                                                                 |                                                                          |

sub-division by its respective area (units of people per hectare of land). All land use maps were reclassified to an adapted version of the water-centric land use classification system developed by Bach et al. (2015) as the VLUS system at its finest level contained more than 100 classes, thereby not allowing for a reasonable analysis to be performed in the context of urban water management.1 In addition to Bach et al.’s (2015) 13 categories, three additional categories (Agriculture – AGR, Forest – FOR and Water – WAT) were introduced (the full list of classes can be found in Supplementary Information – SI Table S1). All geo-spatial analyses were conducted using ESRI ArcMap 10.7.1 geographic information system (GIS) software.

2.3. Analysis of town development patterns

In the first part of this study, we conducted geo-spatial analyses of development patterns within Wangaratta. This included the analysis of: (1) demographic change, (2) parcel-level land use change, (3) neighbourhood composition and (4) land cover change (specifically the change in impervious area). With the help of these results, we subsequently set up and parameterised two SWMM models (explained in Section 2.4) representing the city in 2006 and 2016.

2.3.1. Demographic change

We investigated changes in population density across the study boundary in three sub-divisions: (a) urban extent (Fig. 1a – orange background), (b) growth zones (Fig. 1a – purple polygons) and (c) hinterland areas (all areas neither part of urban extent or growth zones). As the sub-division of census blocks differed significantly between 2006 and 2016 census data sets (with the latter having much finer subdivisions), we resampled the 2006 data onto the 2016 polygons through an ‘Identity’ spatial analysis function in ArcMap. This ensures that a comparison of density changes could be conducted over the 10 years at the parcel level.

2.3.2. Parcel-level land use change

The land use change in the town was analysed using two different methods: (a) a high-level characterisation of the overall change in green or urban-based categories and (b) a more detailed characterisation of change in area of individual land use categories at the individual parcel level. As the VLUS datasets have been rigorously validated and their accuracy assessed both by the original custodians of the data as well as the team, which undertook the project (detailed discussions in Morse-McNabb et al., 2015), this enabled us to perform a consistent reclassification of both time periods and comparison of land use changes at both levels of detail.

In the high level characterisation, we analysed land use changes by first grouping the land use categories (see SI Table S1 for groupings) into ‘urban’ or ‘green’ areas. We compared the 2006 and 2016 Land Use Maps for Wangaratta and identified the areas that fall under each of the following four categories: (1) constant urban area, (2) added urban area/reduced green area, (3) added green area/reduced urban area and (4) constant green area. This analysis allowed us to identify not only the level of growth in urban development that occurred in Wangaratta between 2006 and 2016, but also potential redevelopment and changes in existing land uses. We also queried whether this overall development occurred at the expense of green spaces. Finally, we identified key drivers of increasing urban (reducing green) areas by looking at the breakdown of specific land use categories which make up these different classes (i.e., we identified whether the increase in urban area was driven by residential, commercial or industrial changes – breakdown shown in Table S1). In this more detailed land use change analysis, we calculated the total percentage change in each land use category in the township between 2006 and 2016.

2.3.3. Neighbourhood composition

We used neighbourhood composition analysis to investigate how the proportion of residential, commercial, open space and industrial land uses changed in specific areas in the town. Such relationships are often critical inputs to models of urban development as they determine how certain land uses will cluster around each other (e.g., White et al., 2015). By comparing the two time periods 10 years apart, we can understand whether a fundamental change in the urban fabric took place or whether development patterns remained constant. To create a generalised relationship for Wangaratta, we randomly sampled 80 locations within the urban extent (Fig. 1a), 20 points for each of the four dominant land use categories (residential, commercial, industrial, open spaces comprising parks and nature reserves). Through buffer rings around each point at radii of 100 m, 200 m, 500 m and 800 m, we then calculated the average proportion of each of the four land uses within these rings for both the 2006 and 2016 data sets. Using a radius of up to 800 m is common as it represents approximately the size of area that people consider their ‘local neighbourhood’ and is discussed with further empirical evidence in White et al. (2015). Using several radii allowed us to plot the average distance-decay relationship between different land uses and thus establish how the four major land use types generally cluster around each other within the town. A total of 320 buffer rings within Wangaratta were sampled and analysed. The end result is a plot of the average proportions of each of the different land uses within the four different radial proximities of each other.
2.3.4. Land cover change

The fourth and final analysis of town development patterns is the land cover changes within the region. Specifically, we identified the change in impervious and pervious surface area between 2007 and 2017 by conducting a supervised classification of the obtained aerial imagery. Impervious surface cover is an important environmental indicator (Arnold and Gibbons, 1996) and featured prominently in studies on waterway health (Walsh et al., 2005a; Pauleit and Duhme, 2000) flood assessment (Du et al., 2012; Ozdemir and Elbaz, 2015; Hossain and Meng, 2020) and urban liveability (Alberti, 1999; Bach et al., 2018). Its estimation and analysis from an urban drainage context is inevitable, but will also provide a multi-faceted insight into other potential impacts.

We assumed that the impervious and pervious surface areas in 2007 and 2017 would not significantly differ from 2006 and 2016, respectively given the one-year mismatch in data sets. Obtained aerial images for 2006 and 2016 differed in resolution, but in the interest of consistency, we adopted the same approach on both images. The supervised classification was carried out using the Classification tool in the Spatial Analysis Toolbox in ESRI ArcMap 10.7.1. The classification was conducted on the RGB colour bands of the images. The authors are aware of the pitfalls of using the RGB colour spectrum for the analysis, but had to work within the constraints of available data set as these only contained three bands. To further complicate matters, the 2006 image was captured during the Australian Millennium Drought (the many impacts of which are captured in e.g. Lintern et al., 2018, Saft et al., 2015). The classiﬁcation were made as a ﬁnal step was a broad classiﬁcation of pervious and impervious areas across the entire 333 km2 study area. This step underestimates impervious surfaces and (3) reﬁnement of only the road reserves. Obtained aerial images for 2006 and 2016 differed in resolution, but in the interest of consistency, we adopted the same approach on both images. The supervised classification was carried out using the Classification tool in the Spatial Analysis Toolbox in ESRI ArcMap 10.7.1. The classiﬁcation was conducted on the RGB colour bands of the images. The authors are aware of the pitfalls of using the RGB colour spectrum for the analysis, but had to work within the constraints of available data set as these only contained three bands. To further complicate matters, the 2006 image was captured during the Australian Millennium Drought (the many impacts of which are captured in e.g. Lintern et al., 2018, Saft et al., 2015). The classiﬁcation were made as a ﬁnal step was a broad classiﬁcation of pervious and impervious areas across the entire 333 km2 study area. This step underestimates impervious surfaces and (3) reﬁnement of road reserved areas. The ﬁnal step was a broad classiﬁcation of pervious and impervious areas across the entire 333 km2 study area. This step underestimates impervious surfaces and (3) reﬁnement of road reserves. The ﬁnal step was a broad classiﬁcation of road reserves areas. The step focussed on a clipped area of the aerial image that only featured the urbanised areas (i.e. buildings, roads, landscaping in the form of gardens, lawns and playing ﬁelds, not including water and major densely forested areas). This isolated area of the region was able to better capture the outline of roofs and better distinguish the subtle variations in pervious and impervious areas within the urban fabric. As this distinction was not as clear for the road reserves, a third and ﬁnal classiﬁcation of only the road reserves (clipped based on the VLUIS land use parcels) was undertaken. In the case of the 2006 image, some additional manual corrections to the classiﬁcation were made as a ﬁnal step as it became obvious that some forested areas were still incorrectly assigned the impervious surface category.

From the results of the supervised classiﬁcation, we identiﬁed changes in imperviousness over time at several different spatial levels, from the urban extent, down to the individual growth zones. To further support our analysis and reinforce the validity of the supervised classiﬁcation, we also conducted visual inspection of individual growth zones.

2.4. Investigating the hydrologic impact of town development patterns

2.4.1. Model setup and calibration

After identifying the spatial and temporal patterns in the development of Wangaratta between 2006 and 2016, we constructed a SWMM model (Rossman, 2015) for each time period to identify the impact of the town’s development on the urban hydrology. SWMM is a hydrologic-hydraulic tool that can simulate the runoff generation process within sub-catchments and route ﬂows through piped and channelled drainage networks by solving the St. Venant equations. By using aerial images and Google Street View for quality checking of a pits and pipe data set that we obtained from the Rural City of Wangaratta, we identiﬁed that a signiﬁcant amount of pipe data were missing in upstream and downstream parts of the catchment. As such, constructing a full drainage network was not possible. We therefore developed a “sub-catchment only” SWMM model, where all the pipes were removed and runoff was routed across the surface (roads), connecting the multiple sub-catchments. Taking advantage of automation in GIS, the SWMM model was setup for each land use parcel (land use maps are shown in SI Fig. S1 for the two time periods). Each land parcel was considered a separate sub-catchment, draining into their adjacent road sub-catchment which represented channels that directed stormwater ﬂows to the catchment outlets. This modelling approach and the resulting model for Wangaratta is illustrated in Fig. 2.

For the separate SWMM models representing 2006 and 2016, input parameters were kept constant with the exception of the impervious fraction (further details are available in SI Table S3). These were determined using the aforementioned land cover analysis (see Section 2.3.4) and spatially mapped to the land use parcels (i.e. the SWMM sub-catchments). The average slope of each parcel was calculated using the elevation data (Table 1). Manning’s Roughness values were determined based on recommendations from the SWMM user guide (Rossman, 2015). We only modelled the areas within the study boundary which represented the parcels connected to the drainage system. All other areas outside of the town sub-catchment were removed from the model. Whilst measured runoff and peak ﬂow data were not readily available for calibration, we deemed this less critical as the purpose of our study was to conduct a comparison of the town between the two time periods. As such, ensuring that both models were as consistent as possible in parameter setup and that inputs reﬂected the analyses conducted in the ﬁrst part of this study was prioritised. The authors caution that the comparative results will reﬂect the hydrological changes from a conceptual viewpoint, but that for more realistic insight, measured data sets for the two time periods should be sourced and used to individually calibrate the models.

2.4.2. Simulation scenarios

A total of 40 SWMM simulations were conducted, 20 for each 2006 and 2016, combining four different storm intensities with ﬁve different storm durations. The average recurrence intervals (ARI) selected for analyses included: (1) frequent storms (ARI = 2 years), (2) drainage design storms (ARI = 5 and 10 years) and (3) rare storms (ARI = 100 years). Storm durations simulated for each ARI included: 10, 20, 30, 45 and 60 min. This range allowed us to illustrate the change in the urban hydrology with each storm type considering the urban development. The Intensity-Frequency-Duration (IFD) curves and temporal patterns for the Wangaratta region were obtained from the new Australian Rainfall and Runoff Guideline (Ball et al., 2019). The storm event data used in both 2006 and 2016 SWMM models were the same to ensure that observable changes between these two periods were likely attributed to the urban development (i.e. land cover changes).

2.4.3. Evaluation of model results

We compared the results of the simulations for the 2006 and 2016 SWMM models to identify how the runoff characteristics changed in Wangaratta over this decade. We compared the total runoff for each sub-catchment. We also explored changes in these runoff characteristics in light of the town development patterns that were identiﬁed in the population, land use and land cover change analyses by mapping where the changes in runoff are occurring within the town. We checked for normality of the distribution of the sub-catchment level total and peak runoff using the Kolmogorov-Smirnov test (α = 0.05), and then used the paired t-test (α = 0.05) to identify whether the distribution in change in the sub-catchment level total runoff between 2006 and 2016 was statistically signiﬁcant.
3. Results & discussion

3.1. Analysis of town development patterns

Population changes are shown to have occurred mainly within Wangaratta's urban extent. Fig. 3a provides insight into the spatial changes in population density between 2006 and 2016 whilst Fig. 3b illustrates this scatter at a parcel level based on the urban extent, growth zone and hinterland sub-regions. A linear trendline was fitted through the three scatter plots with an intersect of 0 (Fig. 3b) to illustrate the relative differences in slopes. Overall, it is visible from Fig. 3 that significant increases in population density had occurred within the growth zones and that most of the significant changes (between -24 people/ha to 33 people/ha) occurred within the urban extent. What the scatter plot of the urban extent, however, also illustrates (Fig. 3b-grey) is that, rather than population growth, some reorganisation of the population within the existing area was likely to have occurred (slope of 0.98).

This, however, may also simply be noise, resulting from the changes in census sub-divisions over the 10-year period. As for the hinterlands, only insignificant increases in gross density occurred. This analysis justifies our choice of a case study and indicates that there has been an increase in population in Wangaratta, particularly in the growth zones.

To complement the observable population dynamics, our land use analysis (Fig. 4) indicated that between 2006 and 2016, the urban area in Wangaratta grew. Approximately 2% of the study area in 2016 is urban area that was added since 2006 (Fig. 4a and b). This increase in urban area was predominantly due to increase in residential land use (77% of the increase in urban area). In conjunction with further analysis of census data, these results indicate that an additional 1514 private dwellings were constructed to accommodate for the increase in population. The increase in additional urban area in Wangaratta was greater than the insignificant increase in green space (0.48%) of the study area in 2016 is added urban greenspace (Fig. 4a). It should be noted that the land use analysis showed that the urban development did not
change the water courses. In fact, the growth zones are located away from the watercourses. It appears that the watercourses are shaping the way in which the town has developed, particularly between 2006 and 2016.

The increase in urban area between 2006 and 2016 appears to be a result of the expansion rather than the densification of the town. This is evident in Fig. 4(b) as the added urban areas are mostly located away from the marked town centre. The expansion of the town has largely occurred in a western and southern direction as the town is bound by a major river confluence to the east and a corresponding flood plain which limits growth (RCoW, 2017). The new urban area appears to have been built on agricultural or undeveloped land (Fig. 4c). In the 10-year study period, 2.69 km² of undeveloped land and 1.76 km² of agricultural land were rezoned as residential. Fig. 4(c) indicates that there were minimal changes in the other land uses between 2006 and 2016.

Neighbourhood composition analysis is shown for the four dominant land use types in Fig. 5. Note that in some cases, proportions will
not add up to 100% as there are other land use categories not considered in this analysis, but present within the buffer rings. Generally, if a land use shows a high proportion of itself within close proximity, this will indicate clustering.

Fig. 5a and c show that residential and open space areas are all within close proximity to each other. Logically, given the arrangement of land use within Wangaratta, greater amounts of green space, on average, is observable with increasing distance from most residential areas. Industrial zones are minimal within Wangaratta and mostly located in the south. Although, they are fairly remote from other land uses, we still observe higher proximity to residential land uses than other industrial areas. Notably different to the others is that commercial zones are located in a fairly central location that are accessible to residential areas and are, themselves, highly clustered (seen in Fig. 5b by the equal proportions in residential and commercial land use within commercial buffers). Fig. 5b and d show distinctly low proportions within a buffer radius of 200 m. During the analysis, we noticed that commercial and industrial zones are predominantly adjacent to major highways and roads, which make up the missing land use proportions not depicted on the plots.

Notable changes between 2006 and 2016 are consistent with previous findings and only observable within residential areas and open spaces. Greater densification of residential land and, much less, an increase in green space can be observed through the shift in the curves of residential proportion upwards and decrease in open space downwards. As for the overall development pattern, no major change is observable as both 2006 and 2016 lines run parallel in all cases to each other. As such, we can assume that the city has experienced growth but that no major land use pattern changes occurred in the 10-year period.

Results from the land cover analysis are shown in Fig. 6. Aerial imagery for the growth zones (Fig. 6a) indicates that the town has experienced significant change in land cover from pervious to impervious surfaces over the last 10 years. It is, however, also worth noting that in some cases (e.g. growth zone N), land had already been cleared and prepared for the development which proceeded over the following years. These growth regions relate to the previously mentioned shift from undeveloped/ agricultur al land uses to residential land that occurred between 2006 and 2016. This change in land cover appears to have also resulted in a substantial increase in the impervious areas within the town between 2007 and 2017 (Fig. 5c). The impervious fraction across the five regions increased from 5% in 2007 to 46% in 2017. It is likely that this change in the impervious area in the town will result in a significant increase in urban runoff into the drainage system and less infiltration into the ground. These results indicate that land use changes during the study period have resulted in a shift in land cover in Wangaratta, which may potentially change the urban hydrology. Another interesting point to note is that the most substantial development appears to have occurred north of the railway line, with both northern and southern parts of the urban extent sharing similar levels of imperviousness. Despite attempts to reduce classification noise in the 2007 data set, one can still observe that areas beyond the urbanised districts show specks of impervious areas, which are notably absent in the 2017 classification (shades of red around the outskirts). The level of noise, however, was deemed less impactful in further analyses as these land parcels are mostly unconnected to the main drainage catchment (see Fig. 2 for all connected regions considered in the SWMM model). Fig. 6 indicates that the buffer zones of the waterways in the town remain unchanged between 2007 and 2017.

3.2. Modelling the impacts of urbanisation on surface runoff

The SWMM simulation results illustrated in Fig. 7-left show the spatial changes in total runoff across Wangaratta over the 10-year period. The town centre has a high amount of total runoff (Fig. 7-left). This is to be expected due to the high level of imperviousness in the town centre and is important as this area is in close proximity to existing flood prone areas, such as the Apex Park (Fig. 1b). The growth zones likely have higher total runoff in 2016 as a result of their transformation into housing estates. Urban development has directly resulted in the increase in total runoff in these growth zones, as shown in the example of the Northern Growth Zone (Fig. 7-right). The total imperviousness of the Northern Growth Zone increased from 12% to 52% between 2007 and 2017 (Fig. 6) and this is most likely directly linked to the increase in total runoff of between 2006 and 2016. It should be noted that we were interested in the relative change of total runoff, not the absolute runoff estimates. As we used the same modelling approach for both 2006 and 2016, it is likely that the input data uncertainties will be cancelled out.

Nevertheless, the major growth areas of the town will have been designed with accompanying drainage infrastructure to address the change in sub-catchment characteristics as the impacts of urbanisation on urban hydrology are generally well understood and prepared for. Whereas, the more subtle changes (5–25%), which have occurred across most of the town have often been located in areas that are not driven by major land use and population change (Figs. 3a, 4b). This will not only have implications for the health of the receiving waterway, but also the performance of the town’s stormwater drainage system. These areas are unlikely to have had increased capacity of the drainage system, meaning the existing system must cope with the increased runoff. Therefore, it is important to not only monitor major re-zoning developments, but also the accumulation of the subtle parcel-to-parcel changes (visible in the orange and green scatter within the existing urban fabric in Fig. 7-left).

Simulations of different design storms for 2006 and 2016 indicated that the total runoff in Wangaratta increased between 2006 and 2016 (Fig. 8). There was a statistically significant ($p < 2.2 \times 10^{-16}$) increase in the mean sub-catchment total runoff from 2006 and 2016 in each of the simulations. There has been also a significant increase in the mean total runoff showing that the impervious change has altered the catchment’s response to the same design storm. The distributions of total runoff in each of the sub-catchments shift to have a more positive skew in 2016, suggesting that many sub-catchments have experienced an increase in total runoff (SI Section S3 for detailed statistical results). For example, for the 2-year ARI and 10 minute duration, the skewness of the distribution of sub-catchment level total runoff shifted from $-0.35$ in 2006 to $-0.88$ in 2016. As both the 2006 and 2016 simulations were conducted using the same design storms, this change in total runoff is due to the change in land cover, brought about by population and land use changes in the town. Similar statistically significant ($p < 0.05$) increases were observed for peak runoff when comparing the results from 2016 to 2006 (SI Table S5).

The change in total runoff from 2006 to 2016 appears to be more significant for small frequent storms compared to the longer, more intense storms. This indicates that the effects of urban development are likely to have a more profound impact on frequent smaller storms. This is likely to result in reduced stream water quality (Askarizadeh et al., 2015) and the stormwater drainage infrastructure that is designed for the minor storms may need to be re-designed as a result of the land cover change. Depending on the size of the existing drainage infrastructure, small frequent storm events may be less of a concern in terms of flood risk. However, their cumulative effect can be economically significant (see e.g. Jamali et al., 2020). The increase in total runoff in Wangaratta indicates that urbanisation and growth of the town resulted in changes in total runoff in regions that did not undergo land cover change (see areas outside the identified growth zones in Fig. 7). The land use analysis showed a 2% increase in urban land, however, for a 5-year design storm (from which the residential drainage system is designed – Thomas (2018)) and 10-minute duration, there has been an increase in the median total runoff of 21%. Similarly, as also shown in Fig. 7, even areas outside the growth zones experienced an increase in total runoff in 2016 compared to 2006. This can be explained by the catchment’s sub-
Fig. 6. Land cover change in Wangaratta. (a) Photographs of significant growth regions throughout the town in 2007 and 2017; (b) impervious surfaces in 2007 and 2017; (c) total impervious area in 2007 and 2017 (top) and total impervious fraction for the five growth regions (bottom).
catchments, which are connected and excess runoff is passed to downstream sub-catchments, accumulating towards the catchment outlet.

3.3. Further discussion

The population, land use and land cover analysis and the flood modelling in SWMM has indicated that there has been urban growth in the regional town of Wangaratta and that increases in total runoff are perceivable. This increase in total runoff between 2006 and 2016, particularly in the existing urban fabric. This change in urban hydrology will have a range of impacts, both on the town of Wangaratta itself and the waterways surrounding Wangaratta. Increasing total runoff in Wangaratta is likely to result in decreased water quality and waterway health, as well as geomorphic changes in the receiving waterways (Walsh et al., 2005b). Due to a lack of monitoring data immediately downstream of the urban boundary in the waterways in Wangaratta, we are unable to identify whether there has been perceptible deterioration in water quality between 2006 and 2016. As such, further water quality modelling (e.g., using SWMM - Rossman, 2015 or MUSIC - eWater, 2011) is necessary to quantify the impact of the urban hydrological change on waterway health and geomorphology of the Ovens River, King River and other waterways surrounding Wangaratta. In addition, the change in urban hydrology may result in an increase in pluvial flood risk (Swan, 2010). The increase in urban development may require continual upgrades to the drainage system. The sub-catchment only SWMM model developed in this study was only able to assess changes in hydrology in Wangaratta. However, we recommend that a future study surveys the pits and pipes of the town and then create a full drainage network model for Wangaratta to identify the locations within the town that are experiencing inundation due to urban sprawl, and the key pipes and pits that would need to be upgraded or replaced due to urban development. Data scarcity and uncertainty remains a challenge in such studies, particularly in small towns. In addition to upgrades on the grey infrastructure, e.g. pipes and pits, one should also evaluate the potential of integrating Blue Green infrastructure (e.g. Oral et al., 2020) and other stormwater control measures to mitigate the impact of urban development on the urban drainage systems as has previously been demonstrated in urban catchments (e.g. Walsh et al., 2015). This investigation also highlights the importance of implementing urban greenspace in new urban developments to control the land cover change, or at the very least recognise that developments such as these have consequences on the system. As such, future work should also assess performance of Blue Green Infrastructure in managing the increased total runoff that has occurred as a result of the urban development.

Further work is however required to further explore the effect of increasing runoff on the drainage network of a small town. In this study, we were unable to conduct a detailed analysis of the drainage network of Wangaratta due to the lack of high quality and complete pipe and pit network data. The findings of this study highlight the importance of investment into collecting and maintaining drainage network data in regional towns. To overcome the lack of these datasets, we suggest detailed surveys of pits and pipe networks in regional towns to be conducted so that further stormwater drainage network modelling can be run to identify the key parts of the network that will need upgrading. In order to collect these data, novel image analysis methods (e.g. Boller et al., 2019; Moy de Vitry et al., 2018) could be utilised to develop a drainage network dataset at low cost. Such detailed datasets can then

Fig. 7. SWMM model results for a 5-year ARI, 60-min duration storm showing change in total runoff between 2006 and 2016 time periods (left) and a comparison of total runoff for the northern growth zones (right).
be used to set up a full urban drainage model (i.e. one that also includes the stormwater network) with which pluvial flood risk in Wangaratta as a result of urban growth can be assessed in detail.

There may be development trends in the future that will increase the speed of urban development in small towns like Wangaratta. The COVID-19 pandemic of 2020 may encourage further population movement from urban to regional areas (Farrer, 2020). This is due to the fact that large cities are more susceptible to the spread of epidemics (Alirol et al., 2011) and the current workplace shift to remote working (Preiss, 2020) may potentially lead to more outward movement towards small towns. We suggest that the effect of urban development on urban hydrology should be assessed at other regional towns to assess whether the findings for Wangaratta are common across regional towns in South-Eastern Australia.

Furthermore, forecasts have shown that future climate change is likely to result in an increased frequency of large and intense storms. The results of this study indicate that even small changes in urban development can result in significant changes to the urban hydrology and investigating these nuances will yield valuable insights into how these changes will manifest. Regional towns, particularly in South-East Australia, will undoubtedly experience an increased risk of pluvial flooding, waterway degradation and decline in urban liveability in addition to their ongoing challenges of water supply security if key strategic and cost-effective actions are not taken due to the coupled effects of climate change and future urban development.

Increased impervious areas and their resulting increased susceptibility to adverse weather conditions is not only driven by large population growth and distribution. Subtle parcel level changes, driven by social trends increasing the prevalence of renovating existing houses can have the same effect of increasing the urban footprint and altering the urban hydrology of a catchment. In 2016, more than 61% of houses were renovated or expanded, which was an increase of 57% from 2013 (Holznagel, 2017). Therefore, the increasing number of parcels experiencing small impervious alterations can accumulate to a significant change over the whole catchment, leading to potentially large changes in the urban hydrology of the area, highlighting the importance of monitoring the subtle details of urban development.

4. Conclusion

Across the world, regional towns are developing, and we need to understand how urban hydrology in regional towns is likely to be affected by this development. We used the small town of Wangaratta (South-East Australia) between 2006 and 2016 as a case study. The population, land use and land cover analysis, coupled with the hydrological modelling in SWMM has demonstrated that the combination of small increases in urban (mainly impervious) areas have led to increases in total runoff across the whole town. The urban growth has resulted from an increase in residential land use (e.g. 2% urbanisation) concentrated in growth regions around the town’s outskirts. Our analysis and modelling also indicates that the increase in total runoff is most pronounced for frequent storms of shorter duration, which, although seemingly insignificant, can have a considerable cumulative impact.

These changes to total runoff as a result of population, land use and land cover change may result in geomorphic changes in receiving waterways, poorer water quality in nearby rivers, as well as increased urban pluvial flood risk. The findings indicate that as regional towns develop into the future, stormwater drainage infrastructure needs to be carefully planned and managed to cope with the increased runoff, with the implementation of Blue Green Infrastructure to mitigate the
impacts of urban development on receiving waterways, and the inclusion of green spaces throughout urban regions. Overcoming current data scarcity, particularly when working with consistent historical data sets 10 years apart is an avenue of future research. In addition to urban development, we also expect that climate change will undoubtedly pose an additional significant challenge to regional towns and the waterways near these towns. This makes such studies that couple detailed population-land use-land cover analysis with urban hydrological modelling critical.

**CRediT authorship contribution statement**

**Spencer Browne**: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Anna Lintern**: Conceptualization, Methodology, Data curation, Formal analysis, Writing - review & editing, Project administration, Funding acquisition, Supervision. **Behzad Jamali**: Conceptualization, Methodology, Validation, Formal analysis, Visualization, Writing - review & editing. **Peter M. Bach**: Conceptualization, Methodology, Data curation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition, Supervision.

**Declaration of competing interest**

None.

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**Appendix A. Supplementary information**

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