Systems Analysis quantifies urban stormwater resources and market mechanisms for pricing stormwater and environmental management

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Abstract

This research project builds on previous publications by Coombes et al (2018; 2016) that utilised a Systems Framework of historical big data from government agencies and utilities to identify the water and stormwater benefits of property scale water conservation measures for Australian cities. This project combines additional spatial and temporal detail from the Australian Bureau of Statistics (ABS), Bureau of Meteorology (BOM), utilities, government agencies, local government and latest research in the Systems Framework to quantify the stormwater resource and associated impacts throughout Greater Melbourne. The Systems Framework for Greater Melbourne was enhanced by the addition of higher resolution spatial detail of demographic, socioeconomic, land use, local observations and economic information. The results for the enhanced systems analysis were combined with local and regional costs of stormwater management that include infrastructure, amenity, waterway health and recreation actions. This process is used to estimate the economic and infrastructure requirements for management of urban stormwater runoff, and to develop a new market mechanism for pricing stormwater and environmental management services via impervious area tariffs. The total value of stormwater infrastructure for the Greater Melbourne region ranged from $20,600 million in 2010 to $40,050 million in 2050. The magnitude of additional urban stormwater runoff volumes from Greater Melbourne ranged from 405 GL in 2010 to 700 GL in 2050. Total annual costs to manage stormwater runoff ranged from $1020 million in 2010 to $2003 million in 2050. The impervious area tariff varied from $0.67/m^2 to $1.36/m^2 across Greater Melbourne (average value of $0.86/m^2 and $583/property) and generated decreased directly connected impervious areas, stormwater runoff and management costs.

1. INTRODUCTION

Our cities are evolving into increasingly complex systems in response to economic development and population growth that is driving profound changes to the natural water cycle (Coombes, 2018). The Australian Senate (2015) highlighted the escalating problem of urban flooding and ecological degradation in Australia, and the increasing challenge of climate change. However, it is difficult to define the costs, value, pricing and scope of stormwater management in Australia (Coombes, 2018) and internationally (Tasca et al. 2017). Barry and Coombes (2018) found that these issues cannot be understood or resolved using traditional top down average analysis which is consistent with the observations of Goyen (2000) that variability of urban hydrology is driven by volumes of stormwater runoff from the property scale. The final insights from Meadows (2008) recognized a need for bottom up, hierarchical, self-organizing systems frameworks to understand future challenges and policies to intervene in an increasingly complex world.

The increased proportions of impervious surfaces associated with urban areas is a driver for greater flood risks (Goyen, 2000), declining waterway health (Walsh, 2004) and diminished stormwater quality (Brabec et al., 2002). These impacts define the requirement for stormwater management infrastructure or actions, and the need for revenue to provide and manage infrastructure or management actions. This research project builds on previous publications by Coombes et al (2018; 2016) to investigate the impacts of replacing fixed tariffs for stormwater management and protection of waterways with an impervious area tariff in the Greater Melbourne region. It is envisaged that the impervious area tariff would act as a market mechanism to prompt more economically efficient responses to manage property scale stormwater runoff from directly connected impervious areas that drive the need for stormwater quantity and quality infrastructure throughout the region. Each property owner can choose to pay the impervious area tariff or to reduce the volumes of stormwater runoff discharging from their property. It is proposed that the administrative structure that assesses properties and collects revenue will assist in ensuring that revenue earned from stormwater tariffs is tied to local stormwater management.

Local stormwater management services are currently provided by 36 local governments throughout the Greater Melbourne region and regional management is provided by the bulk water utility Melbourne Water. Local government specifies the provision of drainage infrastructure by developers in accordance with Australian Rainfall and Runoff guidelines and then ultimately manages this infrastructure. Melbourne Water determines the provision of regional hydraulic and water quality infrastructure by developers using catchment based drainage schemes. The operation of local stormwater management by local government is partially funded by revenue collected from general rates based on property values. Operation of regional stormwater management by Melbourne Water is partially funded by a fixed drainage and waterways tariff levied on all properties. These sources of revenue are not tied to stormwater management or locations that generated the revenue or to areas experiencing greater stormwater management challenges, and are often spent for different purposes (Australian Senate, 2015). In addition, the jurisdiction between Melbourne Water and local government is confused for the management of stormwater resulting in increased flood risks (VAGO, 2005) and pollution of waterways (VAGO, 2018).

The full costs of stormwater management are also not well defined for local government or Melbourne Water. Financial reports are often limited to the capital costs of providing drainage infrastructure, such as $0.683 million in Wyndham, $2.5 million in Manningham and $1.17 million in Banyule for 2018. These reported costs do not include maintenance, replacement, operation and staff costs of managing stormwater within local government. The value of stormwater infrastructure in the Greater Melbourne is also not well defined and was estimated to be greater than $11 billion in 2014 in the Melbourne's Water Future by the Victorian government (2014). Similarly, the Essential Services Commission accepted that Melbourne Water's operation, capital and renewal costs of stormwater infrastructure during the 2016 to 2021 period would be $615.6 million, $861.7 million and $641.9 million, respectively (ESC, 2016). Coombes (2002) established that the full costs of stormwater management were about 5% of total asset value and were distributed across different divisions in local governments including roads, parks and gardens, stormwater management and works depots. In particular, a significant proportion of stormwater management costs are actually reported as part of road and depot budgets.

There is a surprising paucity of academic literature on the economics and pricing of stormwater management (Tasca et al., 2017). Impervious area tariffs are utilized in many countries including North America and Germany (Kea et al. 2016). In contrast, there is a substantial body of literature about behavioral responses to water and sewage tariffs with associated economics. Coase (1947) examined the economic effects of uniform pricing, including fixed tariffs, for utility services where the cost to provide services was subject to spatial variation. He found that the marginal costs of utility services were dependent on the quantity of demand and distance from the water source for each consumer. The uniform pricing model for monopoly services is also challenged by technological advances and efficiencies, availability of local resources and scarcity of regional resources (Coombes et al. 2018; Coombes and Barry, 2014). Each household will also have different responses to the price of monopoly services and abilities to reduce water demands or stormwater runoff that are dependent on income, climate and the attributes of each household (Coombes, 2012; Grafton and Kompas, 2007; Dalhusisen et al. 2003). Each household will experience different marginal costs and preferences for utilising services. Uniform prices with fixed tariffs for monopoly water services are a barrier to households seeking economically efficient water resources outcomes that may include water efficient behaviors and appliances, and local water sources (Smit, 2018; Coombes et al., 2018; Deller et al. 2017; Hoffman et al. 2006; Edwards, 2006).

This investigation estimates the spatial costs of stormwater services throughout the Greater Melbourne region in Australia with associated economics of historical tariffs and operating regimes. The economics and water resources impacts of implementing full user pays tariffs for stormwater services is examined using the bottom up Systems Framework model of the Melbourne system described by Coombes and Barry (2014), and Barry and Coombes (2018). The spatial variation in the full costs of providing local government and regional stormwater services is examined.

2. METHODS

This research project builds on publications by Coombes et al (2018; 2016) that utilized a bottom up Systems Framework of historical big data to identify benefits of property scale water conservation measures for Australian cities. The project combines additional spatial and temporal detail from Australian Bureau of Statistics (ABS), Bureau of Meteorology (BOM), utilities, council reports, government agencies and latest research in a Systems Framework to quantify the entire water resource with associated spatial and temporal impacts throughout each city.
The annual reports provided by Melbourne Water and local government were examined to understand the costs and structure of stormwater management throughout Greater Melbourne. These reported provided limited information. Nevertheless, examination of 20 years of data provided in Melbourne Water drainage schemes allowed the determination of the average costs per hectare of development of providing regional hydraulic and water quality infrastructure in each local government area. Surveys of industry costs to provide local stormwater infrastructure were used to determine the costs for provide local government stormwater infrastructure. These local (LC) and regional (RC) costs were combined with projections of population and land use (k) areas from the Victoria in the Future reports (DELWP, 2016) to estimate the total value of stormwater infrastructure (SW) for each local government area (i).

$$SW_i = \sum_{k=1}^{n} LU_k(RC_k + LC_k) \qquad (1)$$

For example, the average costs of providing local stormwater infrastructure for detached, semi-detached and unit dwellings was \$6930, \$4460 and \$690 respectively. The average costs of providing local stormwater infrastructure for non-residential properties were \$31,190. The costs of providing regional hydraulic and water quality infrastructure varied from \$24,570/ha to \$59,870/ha for each local government area with an average value of \$41,640/ha. These inputs and Equation 1 were used within the Systems Framework to determine total local and regional stormwater asset values for each local government area in any year. Written down values of the infrastructure was not used. The costs of renewal, operation, replacement and maintenance of stormwater infrastructure were then assumed to be 5% of total asset value in each year. It was assumed that stormwater infrastructure for new development was gifted to local government and Melbourne water and these costs were not included in operating costs.

The average land area footprint and proportion of impervious surfaces for detached, semi-detached and unit dwellings for Greater Melbourne was 700 m^2 (70%), 400 m^2 (80%) and 130 m^2 (90%). The average land area footprint and proportion of impervious surfaces for non-residential properties was 3130 m^2 (90%). These land area footprints and associated proportions of impervious areas were subject to significant variation across Greater Melbourne. These values were determined from GIS investigations of the spatial data provided by Victorian Land Use Information platform. The price elasticity for uptake of local SW measures was derived from the price elasticities of water use for Greater Melbourne. It was proposed that the current rate of installation of rainwater harvesting on detached properties would increase by 0.38% for a 1% increase in the impervious area tariff. This increase in installation rates was assumed to be 0.13% for a 1% increase in tariff for all other properties. These values were used in the systems framework to estimate value of stormwater infrastructure and the impacts of implementing an impervious area tariff.

2.1 Systems Framework

The Systems Framework described by Coombes and Barry (2015) incorporates local scale inputs within a hierarchical process that is driven from the bottom up. Analysis commences with the local land uses that drive system behaviours and accounts for distributed transactions to simulate spatial and temporal performances of a system. This structure is anchored on detailed "big data" inputs, such as demographic profiles, topography and climate, and linked systems that account for water demands, water supply, sewerage flows, stormwater runoff, water quality, human health, environmental and economic considerations. The Framework is a series of applications for continuous simulation of water and energy balances, and finances that interact to span a hierarchy of relevant spatial and temporal scales from household or land use to city to national and global scales at timelines of one second to 100 years. The process includes multiple replicates of climate sequences and linked responses that yield probabilistic understanding of behaviour and risks. This includes water use and linked generation of wastewater, and stormwater runoff at the local scale, waterways, distribution infrastructure and information at the sub-regional or precinct scale, and regional behaviours and infrastructure such as water extractions from dams and discharges of sewage to wastewater treatment plants and ultimately to environmental receiving waters. An overview of the linked scales utilised in the Systems Framework is presented in Figure 1. A general overview of the hierarchy that corresponds to the conceptual description of the Systems Framework is presented in Figure 2.

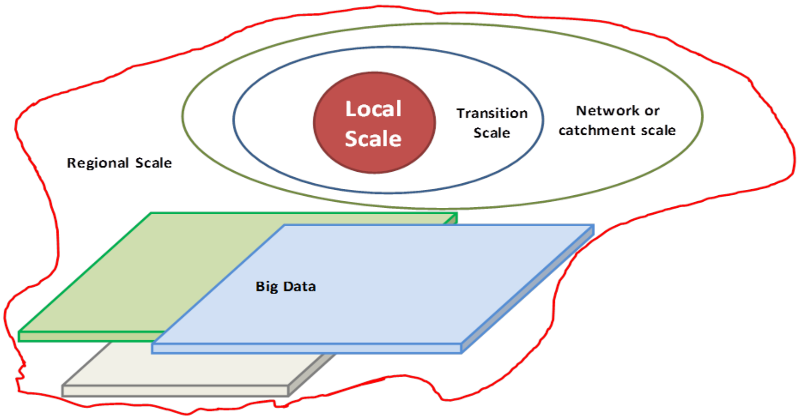

Figure 1: Conceptual overview of the Systems Framework with a focus on the local scale and underpinning big data

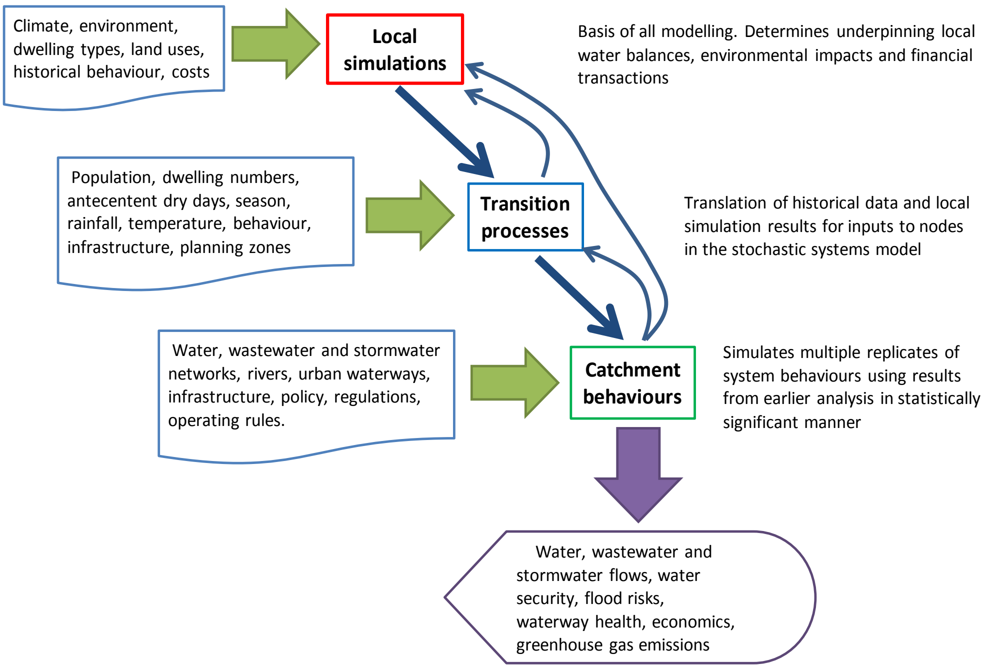

Figure 2: Overview of the hierarchy in the Systems Framework

Figure 1 demonstrates the linked scales that are underpinned by Big Data that are utilized in the Systems Framework. This process allows simulation of linked flows of water, nutrients, finances, sediments and energy throughout a city or a region. These processes range from the details of household behavior and associated water balances (at time resolutions of seconds) to long term forecasting of bulk infrastructure requirements or flood risks or government policies. Figure 2 reveals that the scales of analysis are linked by a hierarchy of processes that are modified by feedback loops. For example, the behavioral response to managing stormwater runoff at the local scale are impacted by regulations or incentives applied at the catchment scale, and climate and economic processes (such as prices) from the regional scale.

2.2 The Greater Melbourne System

The population of the Greater Melbourne region is expected to increase from 4.1 million in 2010 to 8.0 million in 2051 (DELWP, 2016). Analysis of the urban hydrology for Greater Melbourne employed continuous simulation of stormwater runoff from all surfaces at less than 6 minute intervals and discharge into stormwater management networks of 36 councils. Stormwater outputs from each local government area was combined as daily streamflow in regional waterways managed by Melbourne Water. The Werribee, Maribrnong, Yarra, Dandenong and Western Port catchments within the region managed by Melbourne Water are included in the systems analysis as shown in Figure 3.

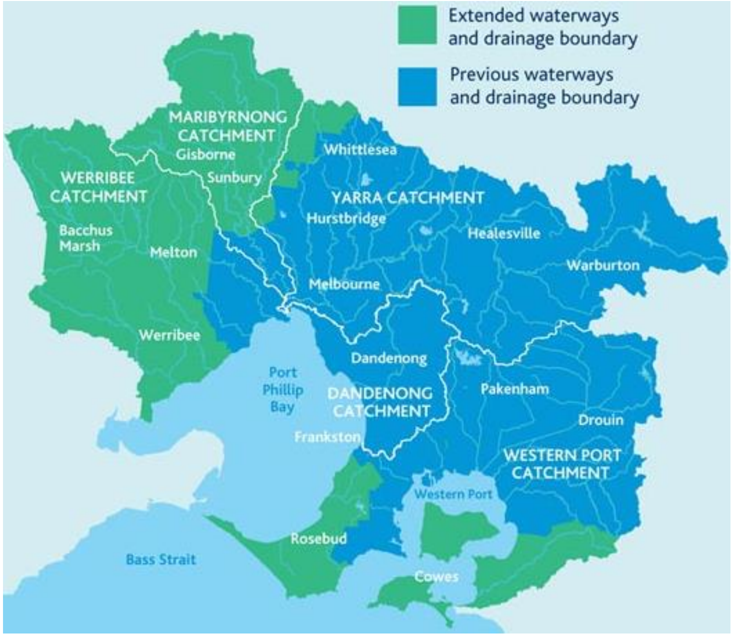

Figure 3: Regional stormwater catchments for Greater Melbourne (Melbourne Water Corporation, 2011)

Stormwater runoff from properties is altered by local water sources such as rainwater harvesting. Coombes et al. (2018) examined data from ABS (2017) to estimate the numbers and installation rates of rainwater harvesting in each local government area in the business as usual (BAU) scenario. An average summary of installation rates for Greater Melbourne is provided in Table 1. The price elasticities of demand was also used to estimate changes in installation rates for rainwater harvesting in the impervious area tariff (Tariff) scenario.

Table 1: Average magnitude and installation **rates of rainwater harvesting at residential properties for Greater Melbourne**

BAU	Tariff
Rainwater harvesting at 21.5% of dwellings in 2010	
8% of renovated dwellings install rainwater harvesting (100 m^2 roof, 3 kL tank, supply toilet, laundry and outdoor)	$Reno_{RWTd} = 8\% + 0.133\frac{\Delta P}{P}8\%$
9% of new (detached and semi-detached) dwellings install rainwater harvesting	$New_{RWTd} = 9\% + 0.38\frac{\Delta P}{P}9\%$
5% of new units install rainwater harvesting	$New_{RWTu} = 5\% + 0.38\frac{\Delta P}{P}5\%$

Note that P is the original price of stormwater management seen by the property owner and ΔP is the different between the new impervious area tariff and the original price of stormwater management. Note that the original price of stormwater management seen by the property owner was assumed to be the MWC drainage and waterway tariff plus the published drainage cost for each local government area. For example, the MWC tariff for a residential property is $100.72 and the published drainage costs for Melbourne City Council equates to about $77. Suppose the property had a directly connected impervious area of 320 m^2, the original stormwater management price would be $0.56/m^2 of impervious area. Note that the minimum MWC Tariff for non-residential properties is $136.

It is acknowledged that most property owners may not be cognisant of these original impervious area costs because there is limited market information about these costs and there is substantial asymmetry of information about stormwater costs and process which hinder the industry. In addition, a property owner may choose from a wide range of potential mitigation measures such raingardens, minimising impervious areas and other vegetated facilities. The analysis assumes that implementation of the impervious area tariffs is accompanied by strong publicity campaigns that ensure property owners are aware of the prices and that local government authorities will count reductions in stormwater runoff volumes as reducing connected impervious areas and the associated tariff.

3. RESULTS

The expected value of the MWC Tariffs, local government (LGA) costs and total costs of managing stormwater in the BAU scenarios are provided in Figure 4.

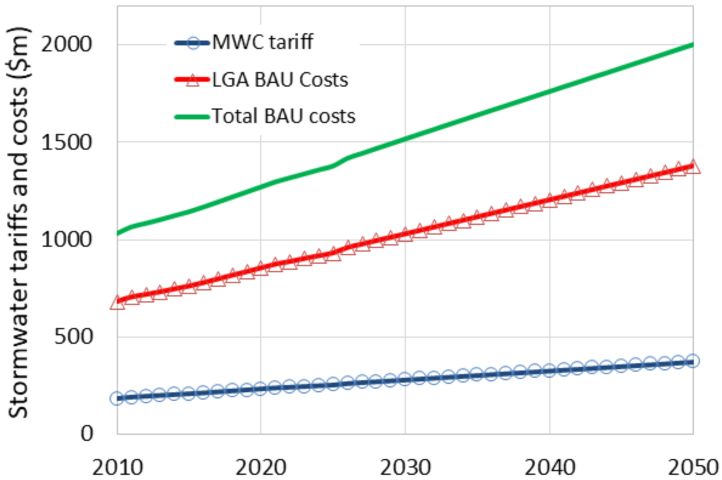

Figure 4: Melbourne Water waterways and drainage tariffs (MWC tariffs), and stormwater management costs for local government (LGA BAU Costs) and for local government and Melbourne Water (Total BAU Costs) for Greater Melbourne

Figure 4 highlights that the minimum value of the Melbourne Water (MWC) drainage and waterways tariff was about $182 million in 2010 and increases to $375 million in 2050. In contrast, the local government costs to manage stormwater increases from $682 million in 2010 to $1380 million in 2050. This represents the full costs to adequately manage stormwater quantity and quality in each local government area and includes operation, maintenance, replacement of assets and associated staff costs that apply across multiple council responsibilities such as roads, drainage and environmental domains. The total local and regional operating costs of stormwater infrastructure ranges from $1030 million in 2010 to $2003 million in 2050.

The spatial distribution of the estimated minimum annual revenue generated by the MWC drainage and waterways tariffs in 2018 is presented in Figure 5.

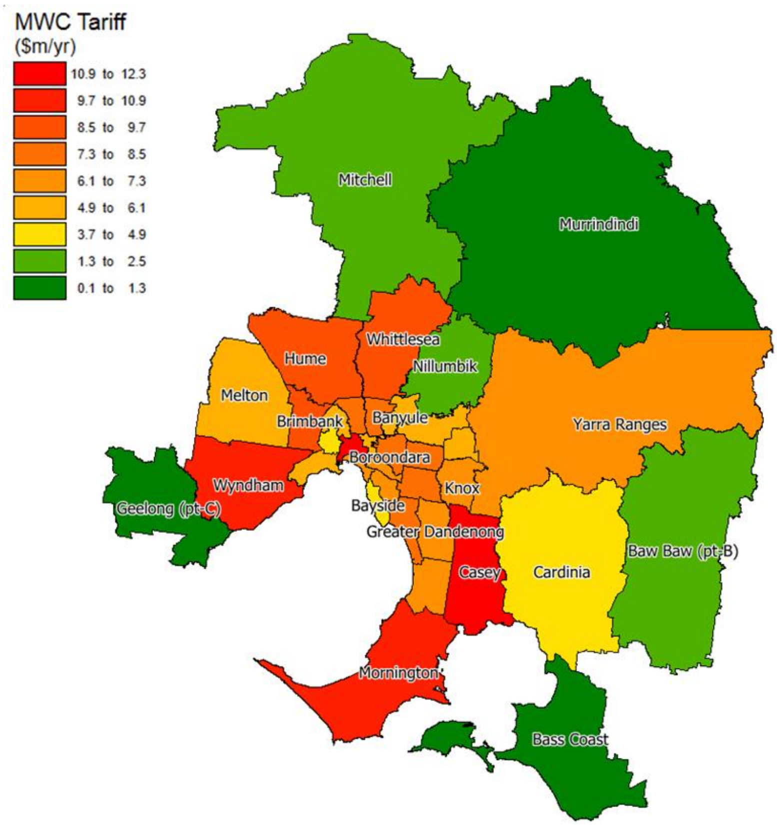

Figure 5: Spatial distribution of revenue generated by MWC tariffs in 2018 for local government areas throughout Greater Melbourne

Figure 5 highlights a strong spatial variation in minimum annual revenues generated by the MWC tariff that ranges from $0.1 million for part of the Geelong area to $12.3 million for the Casey local government area. Higher revenue is currently earned from local government areas in the inner ring with higher density development and in areas with higher population growth.

Spatial distribution of the estimated total value of local and regional stormwater quantity and quality infrastructure in 2018 is presented in Figure 6. Spatial distribution of the estimated total annual operating costs of local and regional stormwater infrastructure in 2018 is presented in Figure 7.

The local and regional values of stormwater infrastructure are presented in Table 2.

Table 2: Local and regional values of stormwater infrastructure for Greater Melbourne

Year	Value ($m)		
	Local	Regional	Total
2010	13,630	6970	20,600
2018	16,330	8030	24,360
2050	27,580	12,470	40,050

Table 2 highlights that the estimated total value of stormwater infrastructure for Greater Melbourne is substantial. These values are consistent with the estimate of the value of local government drainage infrastructure of $11 billion by the Victorian government in 2014 when one considers that pipe drainage infrastructure is only part of the portfolio of infrastructure that manages stormwater (Coombes, 2018). Stormwater infrastructure includes parts of roads (road profile, kerb and gutter) and stormwater infrastructure.

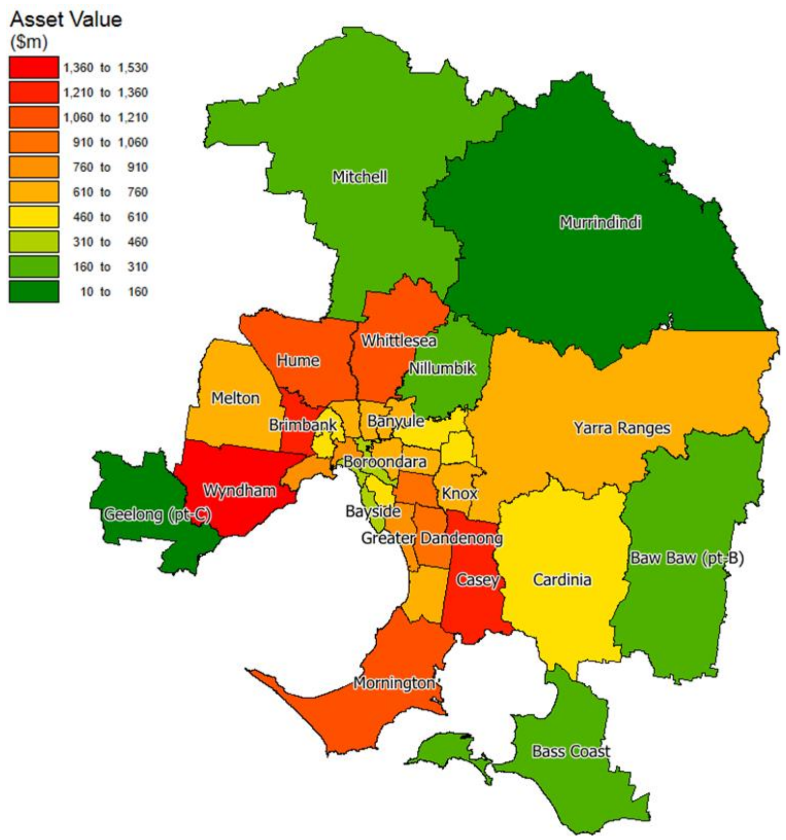

Figure 6: Spatial distribution of the total value of local and regional stormwater management infrastructure for 2018

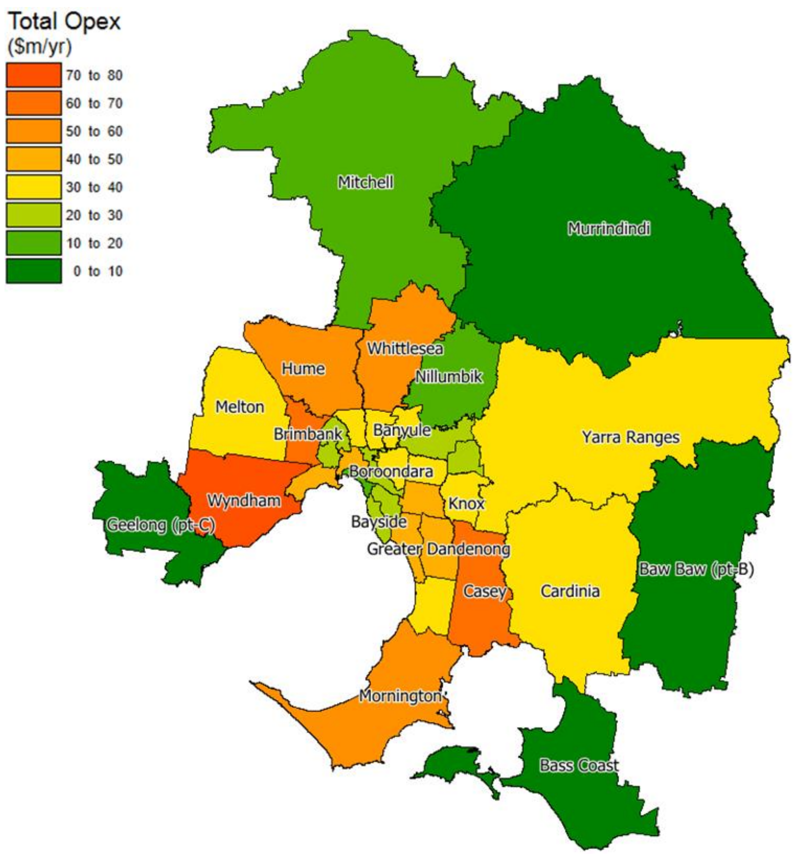

Figure 7: Spatial distribution of the total operating costs of stormwater management infrastructure for 2018

Figure 6 reveals strong spatial variation in total stormwater asset values from $19.2 million for part of the Geelong area to $1526 million for the Wyndham local government area. Local government areas with higher population growth currently have the highest stormwater asset values and councils in the outer ring of Greater Melbourne have lower stormwater asset values. Figure 7 shows substantial spatial variation in total annual stormwater operating costs from $1 million for part of the Geelong area to $79 million for the Wyndham local government area. Local government areas with higher population growth currently have the highest annual stormwater operating costs and councils in the outer ring of Greater Melbourne have lower management costs.

The annual average stormwater runoff volumes discharging from urban surfaces throughout Greater Melbourne for the BAU and Tariff scenario are presented in Figure 8.

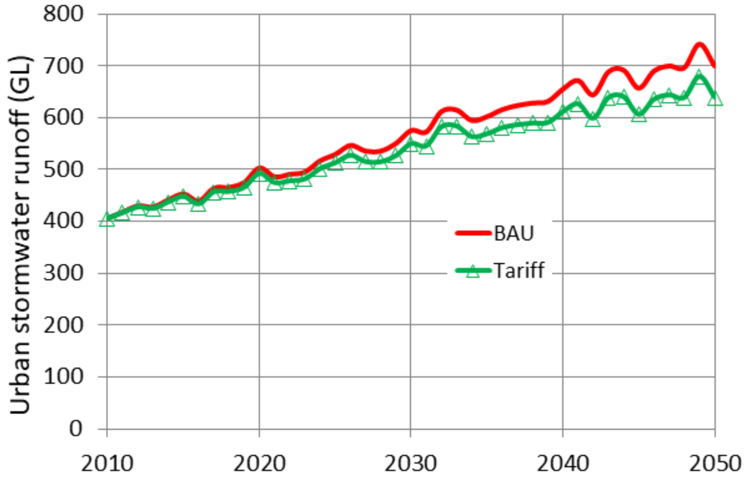

Figure 8: Stormwater runoff from urban surfaces in Greater Melbourne

Figure 8 reveals that the volume of stormwater runoff from urban surfaces in the BAU scenario increases from 405 GL in 2010 to 700 GL in 2050. The additional urban runoff in Greater Melbourne is a substantial resource and an increasing challenge to manage. Replacement of the local government and Melbourne Water fixed charges with a directly connected impervious area tariff reduced stormwater runoff volumes by 59 GL (8.7%) by 2050. The reduced stormwater runoff volumes resulted from properties that installed rainwater harvesting and gardens that divert some of the stormwater runoff for local uses – these local actions reduced the property owner's runoff volumes and directly connected impervious areas resulting in a reduction in impervious area charges. A more complete assessment of potential responses from properties to mitigate stormwater runoff may reveal far greater benefits.

The total area of directly connected impervious surfaces throughout Greater Melbourne for the BAU and Tariff scenario are presented in Figure 9.

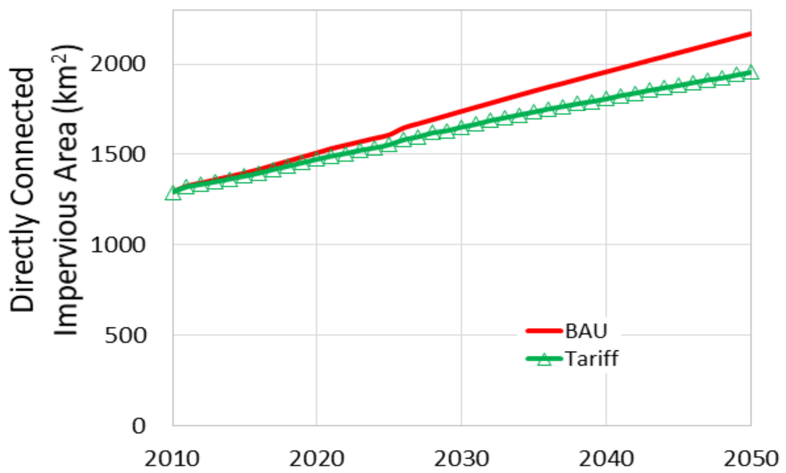

Figure 9: Total directly connected impervious areas for Greater Melbourne

Figure 9 highlights significant increases in directly connected impervious areas from 1290 km^2 in 2010 to 2165 km^2 in 2050. The operation of the impervious area tariffs as a full usage charge has provided an incentive to mitigate stormwater runoff from some properties which has reduced the area of directly connected impervious surfaces on properties by 210 km^2 (9.7%) by 2050. The total annual operating costs throughout Greater Melbourne for the BAU and Tariff scenario are presented in Figure 10.

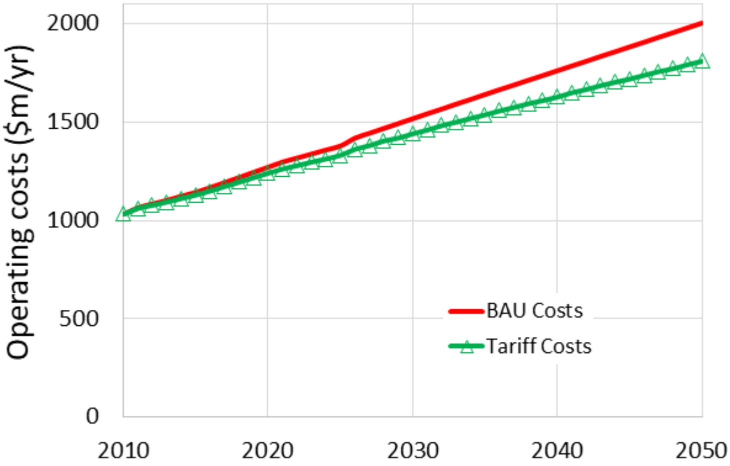

Figure 10: Annual operation costs for stormwater management infrastructure for Greater Melbourne

Figure 10 shows that the operation of the impervious area tariffs have reduced average annual stormwater operating costs by $191 m (9.5%) by 2050. These reduced costs have resulted from property scale stormwater management (rainwater harvesting) that was incentivized by the impervious area tariff. The distribution of impervious area tariffs are shown in Figure 11.

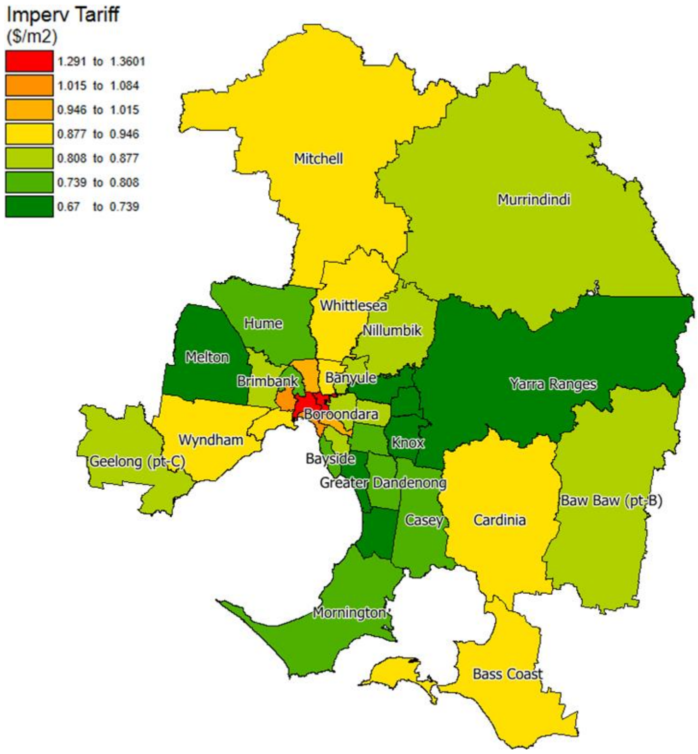

Figure 11: Spatial distribution of the impervious area tariff across Greater Melbourne

Figure 11 shows the spatial variation of the impervious area tariff varies from $0.67/m^2 at Manningham to $1.36/m^2 at Melbourne. The average value of the impervious area tariff was $0.86/m^2.

4. DISCUSSION AND CONCLUSIONS

The impacts of replacing fixed tariffs for local and regional stormwater services with a single impervious area tariff was investigated using a bottom up systems analysis of the Greater Melbourne region. This investigation revealed a paucity of information about the full costs of operating local and regional stormwater infrastructure throughout Greater Melbourne.

Use of data from annual reports published by local government, utilities and government agencies within the Systems Framework facilitated estimated values of local government infrastructure that ranged from $13,630 million in 2010 to $27,580 million in 2050. These values are comparable to values published by earlier government reports. In addition, the values of regional stormwater infrastructure managed by Melbourne Water were estimated to range from $6870 million in 2010 to $12,470 million in 2050. The total value of stormwater infrastructure servicing the Greater Melbourne region ranged from $20,600 million in 2010 to $40,050 million in 2050. The value of stormwater infrastructure within the Greater Melbourne region is substantial which should warrant robust consideration of economic policies to improve the management of stormwater.

The estimated values of stormwater infrastructure was used to determine the total annual costs of managing stormwater infrastructure for the entire region that ranged from $1030 million in 2010 to $2003 million in 2050. There was strong spatial variation of the annual costs of managing infrastructure from $0.1 million to $79 million in different local government areas. The magnitude of these costs were dependent on population size, population growth and population density. The minimum revenue generated by the MWC drainage and waterways tariffs ranged from $182 million in 2010 to $375 million in 2050.

Application of an impervious area tariff resulted in charges that ranged from $\$0.67/m^2$ to $\$1.36/m^2$ across Greater Melbourne with an average value of $\$0.86/m^2$. The average cost of the impervious area tariff across all properties was $573. It is important to note that the value of this tariff has been set to account for the revenue required for pay all costs of stormwater management throughout the region. These full costs were unknown and this study has provided a first estimate of these values.

Replacement of fixed tariffs and general rates with an impervious area tariff has incentivized local storm water solutions that reduced directly connected impervious areas by 210 km2 (9.7%), annual storm water runoff volumes by 59 GL (8.7%) and annual average management costs by $191 million (9.5%) by 2050. It is likely that these benefits have been under-estimated because the full range of lot scale storm water management options were not included in this preliminary analysis, the impacts of the storm water “usage” tariff on the entire water cycle is not presented in this paper and the further research is needed to understand the likely behavioral responses to this type of economic market mechanism. A significant benefit of the proposed impervious area tariff is that it will generate more transparent understanding of storm water costs and funding arrangements. Realizing this benefit will require an improved administration structure that may involve significant transactions costs to establish.

5. ACKNOWLEDGMENT

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