LOSING STORMWATER: 60 YEARS OF URBANISATION AND REDUCED DOWNSTREAM FLOW

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ABSTRACT: *The potential for stormwater to supplement traditional water supplies from upstream catchments or groundwater is high, with claims that the quantity of additional runoff from impervious surfaces in a modern city in a temperate climate is greater than the total potable water demand. Ballarat, an inland city of approximately 100,000 people in south-eastern Australia, has many attributes necessary to exploit this opportunity. Given the doubling of population, tripling of residences and 90% increase in average residence size over the past 60 years, over which time flow data is available for the downstream waterway, it might be expected that the flow in the river downstream of the city within the catchment would reflect additional stormwater runoff. However, no increase in flow was detected between 1957 and 1996 while flow over the past 20 years has reduced by 60%. A water balance shows this decrease was not due to extractions as the stream has been a consistent net receiver of water from other catchments. Modelling data from the Australian Water Resources Assessment indicates that the reduction in streamflow is double what might be expected due to climatic variations. Between 1957 and 1996 there was no significant difference between modelled runoff and actual flow, however from 1997 onwards there is a significant divergence. While lower runoff may be expected during the period of drought, the rainfall-runoff relationship does not return to previous levels during latter years of rainfall. The effect is greater during higher flow months, which has significance when identifying potential additional water resources. Base flow has been reduced to the point where dry weather flow is reliant on waste water treatment plant and mine discharge. This study indicates that while impervious surfaces generate higher runoff which can cause environmental damage, making stormwater an attractive water source, consideration must be given to the impacts on the whole catchment when assessing alternative supply options.*

KEYWORDS: Stormwater, Streamflow, Urbanisation, Ballarat, Victoria, Australia.

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1 INTRODUCTION

Integrated Urban Water Management offers multiple benefits that span improved amenity in the lived environment, better environmental outcomes for receiving waterways and additional water resources that can supplement, or even replace, current supplies. The effects of urbanisation around increasing the magnitude of peak flows, a higher frequency of flow peaks, and the resultant impact this has on the morphology of receiving waterways and the riparian landscapes have been well established [1-3]. However, while the peak runoff from urban surfaces is known to increase, the total impact on the streamflow regime is more variable and less well understood [4]. For example, it has been shown to decrease when groundwater contribution is significant [5], or might have little change [6] or increase significantly [7], depending on the catchment and its associated circumstances. The implementation of IUWM is increasing and this will begin to have impacts at the municipal scale. While there is good evidence on implementing Water Sensitive Urban Design at the development scale, and how this can ensure storm flows do not exceed pre-development level, IUWM is typically expected to deliver other benefits such as reducing demand from centralised potable supply systems. Initially the reduced demand may be due to a reduction in external watering requirements for example, as runoff naturally irrigates roadsides and parkland, and further on from storm water re-use schemes. The additional runoff due to impervious surfaces can be used to provide water and therefore potentially maintaining the pre-development flow regime in the receiving waterway.

To determine how significant the impact of IUWM could be on the water supply, the effect of increasing urbanisation on downstream waterway flow must be known so the potential additional resource can be calculated. While there have been urban water balances which determine this, they generally use the increased stormflow calculated from the area of impervious paving to calculate the additional resource [8-10]. This does not allow for all the changes in the water balance and the impact of urbanisation on the river systems. To consider the total impact of IUWM, the stream flow of the receiving waterway ideally needs to be directly measured. Actual changes in streamflow over time can then be compared with expected changes due to known causes, and the difference then attributed to urbanisation and modifying stormwater management techniques.

Including the downstream flows will 'close' the water balance, giving greater certainty to estimates which calculate run off based on impervious surface area. To do this the data required includes;

- Precipitation on the city and catchment
- Bulk transfers of water in/out of the city
- Water consumption within the city
- Treated wastewater volumes to receiving waterways
- Abstractions from waterways
- Streamflow data for the receiving waterway

Annual data has been used in this study for calculating the system water balance. Using annual data helps to remove seasonal effects while still providing adequate decadal water balance analysis. Seasonal variations, peak flow magnitude and frequency analysis, and rate of change are all important determinants of impact for urbanisation and IUWM and can be measured using a different time scales. However, when assessing the impact that urbanisation has had on the total water resource available, particularly in the context of volumes available to supplement supply, an annual time frame is considered appropriate.

While neither the type of data gathered nor the use of a relatively simple water balance is unique, the application of this to determining the impact of urbanisation on a receiving water seems not to have been widely applied. It is important to be able to measure the relative success of IUWM over the long term, and the analysis presented in this paper helps provide new insights into IUWM success.

2 METHOD

To ascertain the applicability and viability of using an annual water balance methodology in conjunction with river flow data a case study is used. The potential for capturing additional stormwater runoff to supplement water supply is particularly appropriate for a growing inland city in a temperate climate where the downstream waterway is accessible.

2.1 BALLARAT

Ballarat is a city of in south eastern Australia (37.5622° S, 143.8503° E) of 103,964 people in 2016 [11]. It is facing many of the water issues that are confronting communities throughout the world. It has grown from 50,930 people in 1957, and is forecast to continue growing to 140,000 people in 2030. Existing surface water supplies are limited and there is a reliance on inter-basin transfers for supply[12]. Groundwater has been used to supplement supply in times of extreme drought. Harvesting stormwater using Managed Aquifer Recharge has been trialled as a potential alternative water supply[12]. Ballarat is in a temperate climate zone, with average rainfall (1908 – 2016) of 689.9mm close to the city centre, but higher falls, 848.5mm, (1882 – 2016) within the water catchment area [13]. The average maximum temperature in the hottest month (February) is 25.2°C, while during the coldest month (July) this drops to 10.1°C, and the average minimum temperatures for these months are 10.9°C and 3.2°C respectively. There is an occasional sprinkling of snow which rarely settles and has no different effect on the water balance than rain.

Ballarat's first European settlement was in 1837, but the population exploded soon after when gold was discovered in 1851[14]. A water supply was established in 1856, with the Ballarat Water Board forming and thus consumption information became available continuously from 1882 [12]. The location of the city is primarily due to the gold rush, and it sits in the upper reaches, and at the intersection of, five separate catchments, which makes it a less than ideal location for a water supply to be established upstream of the city (Figure 1).

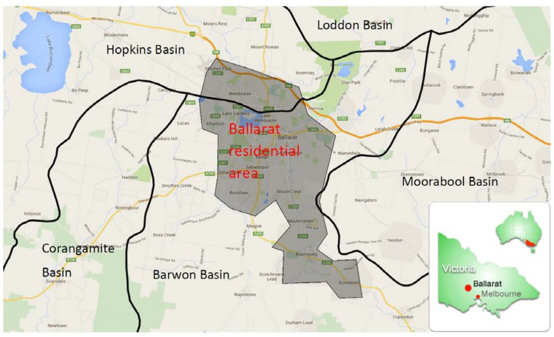

***Figure 1:** Ballarat location and water basins*

The waterway from which the initial supply was taken, and into which the majority of stormwater and wastewater now flows, is the Yarrowee River, which then becomes the Leigh River and is part of the Barwon catchment. However, from the 1860's reservoirs have been established in the adjoining Moorabool catchment, with water supply security now also dependent on bulk transfers from the Goulburn catchment (via the Loddon Basin) in northern Victoria via the 'Goldfields Superpipe'. The sewage collection system commenced in 1922, and the initial treatment plant, Ballarat South, discharges to the Yarrowee River, and currently processes about 2/3 of Ballarat's wastewater. The 'Ballarat North' treatment plant has processed the remaining waste since being established in 1972 and discharges into the Hopkins Basin. In addition to the treatment plants, there is also regular discharge from Ballarat Goldfields where pumped groundwater from mine de-watering is transferred into the river. Groundwater was also used to supplement supply during the Millennium Drought (1997 – 2008). A number of monitoring stations have been established on the Yarrowee River, however, the current one on the Leigh River at Mt Mercer (233215) has been operating continuously in its present form since 1956[15]. This is approximately 29 km south of Ballarat, with a total contributing catchment area of 593 km^2. While a river measurement point closer to the city would have been more sensitive to the effect of urbanisation, measurements from this gauging station still demonstrate the overall impact on the upstream catchment due to growth and spread of the city. There is rural farmland and significant peri-urban development throughout the catchment, although there is no irrigated farming and the licensed extractions from the river are relatively small and for stock and domestic purposes only.

A growing city in a temperate climate with 60 years of data available on transfers into and out of the city boundaries and the river from a variety of sources, including water treatment plants and remote catchments, enable a water balance to be constructed that can allow an analysis of the impact of urbanisation on the receiving waterway.

2.2 WATER BALANCE

The Yarrowee River Flow as measured at Mt Mercer is comprised of a number of components as expressed in Equation (1).

$$Q_Y = Q_{CR} + (Q_M + Q_{GF} + Q_{SP} + Q_{GW}) - (Q_N + Q_E) - S_Y \quad (1)$$

Where

Q_Y = Yarrowee River Flow (recorded)

Q_{CR} = river flow due to rainfall on the catchment (stormflow + baseflow)

Q_M = transfers from the Moorabool catchment
Q_{GF} = Ballarat Goldfields mine discharge
Q_{SP} = transfers from remote river basins (Superpipe)
Q_{GW} = managed transfers from groundwater
Q_N = catchment rainfall transferred out via the north treatment plant
Q_E = extractions from the river
S_y = change in storage of reservoirs from the Yarrowee catchment

This water balance equation is represented schematically in Figure 2.

The river flow due to rainfall on the catchment is the effective runoff from the catchment and is the rainfall less evaporation, transpiration, consumptive use and changes in groundwater storage. Q_{CR} is the variable that will most change due to urbanisation and the associated increases in impervious catchment area. Due to the distance of the gauging station downstream of the urban area, the runoff from the overall catchment can be thought of as two components – urban and rural runoff. The amount of streamflow for a given rainfall from the urban catchment is obviously different compared with the rural. It will have a higher runoff coefficient, and the area of this is increasing while the area of the rural catchment correspondingly decreases over time. As there is data available for all other components, Equation (1) can be rearranged to calculate Q_{CR} in Equation (2).

$$Q_{CR} = Q_Y - (Q_M + Q_{GF} + Q_{SP} + Q_{GW}) + (Q_N + Q_E) + S_y \quad (2)$$

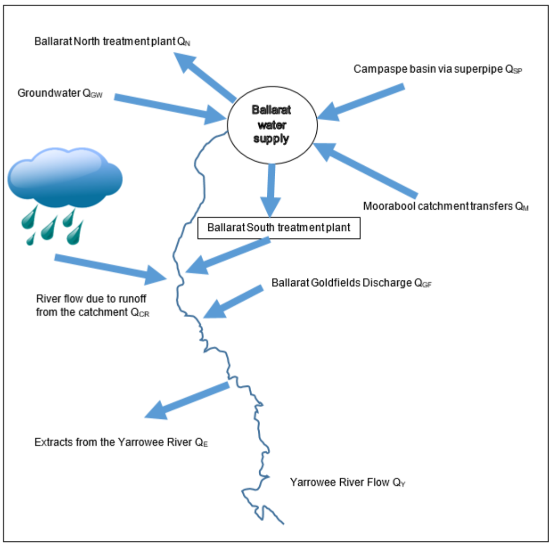

Figure 2: *Water transfers to and from the Yarrowee River*

Calculating the river flow due to the rainfall on the catchment over time should demonstrate the impact of urbanisation on the annual average hydrologic response of the catchment.

2.3 HYDROLOGIC RESPONSE

The hydrologic response is the way in which rainfall is translated into runoff and stream flow in the catchment. While this can include all the temporal effects which are important in understanding the full impact of urbanisation, the annual average hydrologic response (HR_{AA}) will demonstrate the change in overall river flow volume due to rainfall.

$$HR_{AA}\ (\%) = Q_{CR} \times 100/(\text{Rainfall} \times A) \quad (3)$$

Where
HR_{AA} = Annual Average Hydrologic Response
Q_{CR} = river flow due to rainfall on the catchment (ML/year)
Rainfall = average rainfall over the catchment (mm/year)
A = catchment area (km^2)

Calculating HR_{AA} accounts for the direct effect of rainfall on river flow. Obviously, river flow will be lower when rainfall is less. However, if the runoff is greater due to urbanisation, HR_{AA} will increase.

2.4 HYDROLOGIC MODEL

Calculating the Annual Average Hydrologic Response may demonstrate the change in the rainfall, runoff relationship over time, however it is known that this relationship is also dependent on rainfall. Therefore, results of hydrologic modelling and the expected runoff from the catchment are compared with the actual river flow over time. Changes in the difference between the hydrologic model and the actual results will provide an indication as to the effects of urbanisation within the catchment.

The Australian Water Resources Assessment Modelling System (AWRAMS) is a grid based, integrated hydrologic mode developed by the Australian Bureau of Meteorology (BOM) and Commonwealth Scientific and Industrial Research Organisation (CSIRO) [16-19]. It can provide evapotranspiration, soil moisture at depths to six metres and runoff since 1911 in Australia based on unimpaired catchments. It has been calibrated and validated using 595 river basins with common parameters used for the model in all areas. While this broad scope gives strength in the amount of data available and robustness, it can mean local calibration issues are not considered, however published calibration results indicate performance is similar to locally calibrated models[17].

Data was provided by the BOM for the Barwon River basin (of which the Yarrowee River is a tributary) for daily, monthly and yearly intervals from 1911 until 2016.

If a difference between the actual river flow and the predicted runoff was to change over time, it may be possible to relate this to the changes in the catchment, and in this case demonstrate the impact of urbanisation on the total river flow. The Yarrowee River flow anomaly has been calculated by subtracting the actual river flow from the predicted runoff.

$Y_{RA} = Q_{pred} – Q_{CR}$ (4)

Y_{RA} = Yarrowee River Anomaly (ML/year)
Q_{pred} = Runoff predicted by AWRAMS (ML/year)
Q_{CR} = river flow due to rainfall on the catchment (ML/year)

3 RESULTS AND DISCUSSION

3.1 WATER BALANCE

The Yarrowee River flow, as measured at Mt Mercer downstream of Ballarat from 1957 to 2016 is shown in Figure 3. The river flow due to rainfall on the catchment (Q_{CR}) is also shown, and can be seen to have a similar profile. Transfers into and out of the river have resulted in a nett gain of 6,000 ML/year of flow in the Yarrowee, primarily due to transfers from the Moorabool and other systems to maintain Ballarat's water supply. Water also exits the broader Ballarat city boundary via the Ballarat North treatment plant, a proportion of which has come from Yarrowee catchment and the remainder transferred in from surrounding basins. Overall, while the transfers do vary from year to year depending on the availability of various forms of water, the overall impact is relatively constant, with the graphs of actual and calculated river flow being almost indistinguishable on the scale of the overall flow (Figure 3). Understanding that the effect of transfers do not substantially alter the shape of the annual river flow versus time relationship, does enable later analysis at shorter time steps for which river flow data can be used even though some of the water balance information is only available in an annual format over the time period studied.

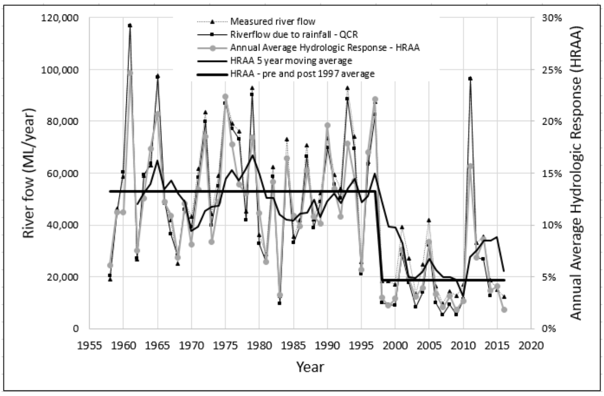

Figure 3: *Yarrowee River Flow and Annual Average Hydrologic Response*

Despite the population of Ballarat increasing from 51,000 to 78,000 between 1957 and 1996 [11], and the number of residences doubling from 18,000 to 37,000 in the same time [12], there was no observable change in river flow during that period. A best fit using linear regression has an R^2 value of only 0.01, and a difference of means test shows the average runoff reducing, but this is not statistically significant. However the last 20 years has seen a significant reduction in the river flow. The timing of this change has been determined by the production of a residual flow curve (Figure 4). The shape of the residual rainfall on the same chart is very similar.

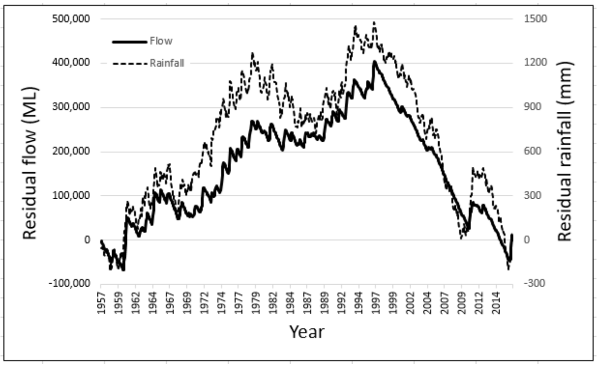

Figure 4: *Yarrowee River Residual Flow Curve and Residual rainfall by month*

Unsurprisingly, the river flow dropped significantly at the time of the commencement of the Millennium Drought, which in Ballarat lasted from 1997 until 2010. However, the question remains whether or not urbanisation significantly altered the downstream waterway flow quantities. Although the river flow has reduced markedly, the impact of reduced rainfall can be considered when assessing water availability against what may have been expected without development.

3.2 HYDROLOGIC RESPONSE

To investigate the impact of urbanisation of river flow while accounting for rainfall variations, the Average Annual Hydrologic Response (HR_{AA}) is also shown in Figure 3. Perhaps more surprisingly, this also shows a similar pattern to the river flow data. While the average annual rainfall in the past 20 years is 84% of that from 1957 – 1996, the river flow fell to 34% of what had occurred during the prior time period. This indicates a significant change in the rainfall - runoff relationship during this time.

In the first 40 years of recorded data, 13.2% of rainfall became river flow, however, in the most recent 20 years the river only received 4.9% of the rainfall. It was expected that due to urbanisation we would see an increase in the rainfall - runoff relationship. This has obviously not occurred. Changes in rainfall and temperature are also known to alter the rainfall - runoff relationship as soil moisture and evaporation rates will also be effected. To determine whether the change in river flow is an expected response given the conditions in this catchment the modelling from AWRAMS was used.

3.3 HYDROLOGIC MODEL RESULTS

During the initial 40 year period of recorded flow data for the Yarrowee River, there is good correlation between the modelled runoff data from AWRAMS and the actual measured flow. A difference of means test shows no statistically significant difference at a 99% Confidence Interval (CI) between the average actual and modelled results. Variations which do occur, which from Figure 3 can be seen to be during the highest and lowest flow years, may be due to the influence of reservoirs in the catchment. The average flow results and the similarity in the annual flow charts would appear to confirm that the model is a reasonable representation of what is occurring in the catchment.

Over the past 20 years, the modelled runoff has predicted 16,500ML/year more runoff than has been measured in the river (Figure 5). A comparison of means test shows that the modelled runoff between 1997 and 2016 is statistically significantly different at a 99% CI to the actual river flow. The AWRAMS which had accurately predicted the river flow between 1957 and 1996 did not replicate this for the 1997 – 2016 period, suggesting there has been a change in the rainfall-runoff relationship

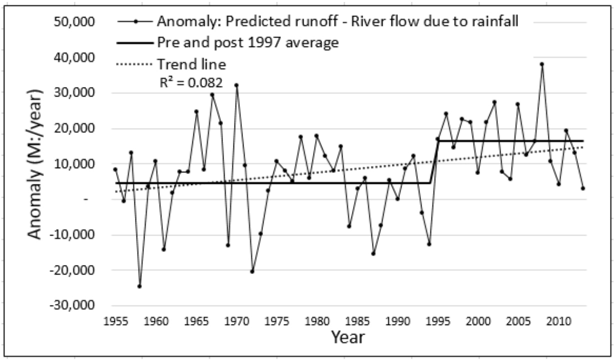

Figure 5: *Yarrowee River Flow Anomaly*

With a steady rate of increase in population, housing and impervious area within the catchment, if urbanisation was the driver of this change it may be expected that a continuous change over time would occur. This is not happening, as can be seen by the linear trend line which shows no significance (R^2 = 0.082). It would also be expected that changes in urbanisation would lead to a greater river flow compared to that predicted from an unimpaired catchment, a negative number for Y_{RA}. The results however are showing less river flow than predicted. This suggests that the impact on the catchment which have resulted in river flow reductions are far greater than any increase in river flow due to urbanisation.

3.4 SEASONAL EFFECTS

While annual data is useful to assess overall water availability from a stream, having identified a major shift in the rainfall – runoff relationship, understanding the seasonal effect of this change is also useful. To do this, the year has been divided into four periods, determined by high and low average river flows. They are August – October (high), November – January, February – April (low) and May – July, lagging the traditional season definition in Australia by one month but accurately reflecting the phases of river flow. For each of these periods the HR_{AA} has again been calculated (Figure 6).

This demonstrates that while the dry, summer-autumn period does not show a significant change (and the trend may in fact be a small increase in flow over this time, although a linear correlation has an R^2 value of less than 0.01 and a difference in mean test between the earlier and later periods is statistically insignificant), there has been a severe dampening of flow in the post-dry period from May to July, and during the time when the highest river flows occur from August to October there has been a significant decrease in stream flow, which reflects the overall flow pattern. This observation is consistent with others who have described seasonal shifts in runoff due to climate variations since 1997 [20].

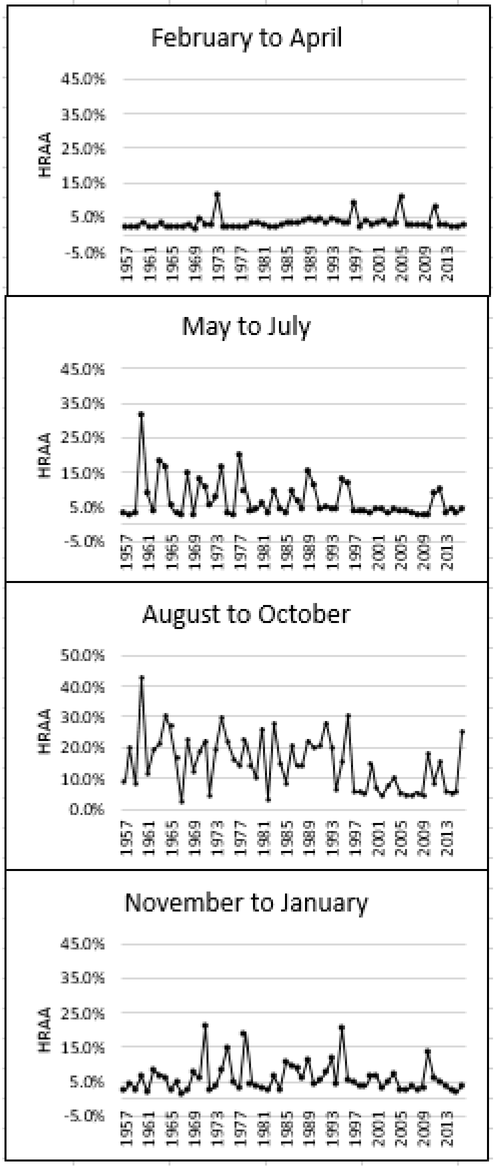

***Figure 6**: Annual Average Hydrologic Response for wet, dry and shoulder periods by year.*

The positive trend that is visible in the dry period data may be the only indication of an increase in runoff over time that could be related to urbanisation. The effects on the remainder of the catchment may not be noticeable during the warmer, drier periods as there is relatively low runoff anyway. However, the reduction in runoff over the wetter periods is far greater than any increase in runoff during the drier months.

3.5 DRY WEATHER FLOW

One important variable effected by changes in the rainfall runoff relationship is dry weather flow – the flow which is not the result of a storm event and can therefore be related to base flow. While there are many variables such as peak flow, rate of change and frequency of flow events which can be used to describe river flow characteristics, and this paper is primarily considering the impacts on the overall flow, the seasonal effects and any changes to the temporal flow regime has a signifcant impact on the availabity of water for alternative use and is therefore of interst here also. It has been calculated, using the empirical Equation (5) [21],

$t\ (\text{days}) = 0.827 x A^{0.2}$ (5)

where A= catchment area (km^2)

that the expected time for a storm event to impact runoff in the Yarrowee catchment is three days. Therefore, the flow for all days which are the fourth or more consecutive day of no rain has been compared. The top and bottom 10% of these days by flow has been excluded to remove anomalies, such as water released from reservoirs, the inexact nature of the three day estimate or potential data errors, leaving 4,088 days which meet the criteria over the sixty year period. There are two notable results (Figure 7). Firstly, the dry weather flow from 1957 – 2016 had a significant peak during the high flow months, more than four times the flow in the drier months. This does not occur during the 1997 – 2016 period. Secondly, despite the average dry weather daily flows being higher during 1997 - 2016 than for the pre 1996 period for many months of the year, it is essentially equal to the daily flow from the Ballarat South Wastewater Treatment Plant (WWTP). The difference between the total river flow and WWTP discharge demonstrates the dry weather flow is now almost entirely dependent on the discharge of the treatment plant for a number of the summer months.

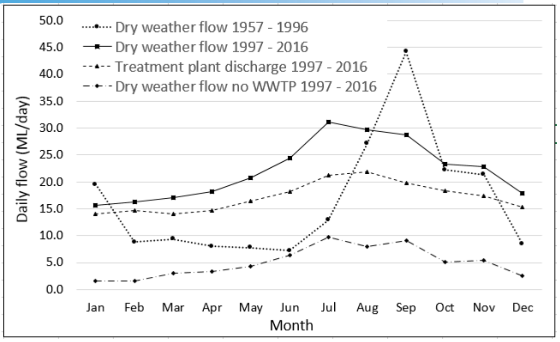

Figure 7: *Yarrowee River dry weather average daily flow and flow from WWTP*

3.6 POTENTIAL CAUSES

Despite a significant increase in the size of the urban area and percentage coverage of impervious surfaces in Ballarat, no increase in the flow of the Yarrowee River downstream of Ballarat is measurable in the years from 1957 – 1996, and a significant decrease in flow has occurred over the past twenty years. This decrease has been greater than would be expected based on modelling of the catchment and the climatic conditions experienced. While stormwater runoff modelling will likely show increased flows from the growth in impervious surfaces of a city, if this is to be captured and used without having a negative environmental impact, the whole-of-catchment effects must be understood including changes to the actual river flow. While this work demonstrates the importance of considering the total catchment, there are a number of unanswered questions which remain to be addressed.

Ballarat may be a unique case where the impact of urbanisation cannot be detected in the river flow. However, studies have shown that about half of Victoria's catchments have suffered permanent changes to their runoff producing characteristics post Millennium Drought [22]. While that work did not consider urban catchments, if the implications are that significant reductions are occurring due to other factors, rivers downstream of cities may in future become more reliant on urban runoff for their sustainability, complicating some aspects of IUWM and the benefits of storm water capture and use. Further comparisons of other cities and their waterways and the changes in downstream flows are required to determine if the observations about Ballarat have wider implications.

During the Millennium Drought, the use of water tanks for use in gardens and flushing toilets was encouraged. The widespread installation of tanks and their aggregated effect may have resulted in a change to the total amount of stormwater runoff from the urban area.

Ballarat, as do many regional and major cities, has a significant peri-urban fringe. Many of the land holdings have installed small farm dams for aesthetic, stock and domestic reasons, and this has been shown to have a significant effect in other catchments[23]. The impact of these on the Yarrowee River flow must be understood. Small farm dams can capture much of the water from small rain events, directly countering one of the benefits of harvesting stormwater where even these can produce an available resource [24]. If this is widely true, then small dam impact must be considered when assessing water availability from broader urban catchments.

The impervious surfaces throughout a city prevent infiltration and therefore potentially reduce the groundwater aquifer recharge [5]. Rapid storm flow runoff is also known to contain a significant amount of water that is not from the current storm event, the so called 'old water paradox' [25]. The effect of urbanisation on groundwater recharge, and the impact this has on the hydrologic response of the river must then be considered when assessing the potential for storm water harvesting.

The quantification of these potential causes in the reduction of the flow in the Yarrowee River is the subject of ongoing work, as is the comparison of Ballarat to other cities.

Integrated Urban Water Management, including the use of stormwater, is being encouraged [26]. The current methods for assessing the available quantity of stormwater for potential reuse is to model the additional runoff from impervious surfaces. Without closing the water balance and understanding the flow of downstream receiving waters, a true assessment of the success of IUWM cannot be made. A framework for monitoring IUWM outcomes must be established so that progress can be measured and unwanted effects do not unintentionally occur from programs that are established based on their seemingly positive outcomes.

4 CONCLUSIONS

Integrated Urban Water Management has the potential to mitigate both the requirement for additional water supplies and the environmental impact on waterways within and downstream of cities. One of the commonly understood tenets of IUWM is the capture and use of stormwater flow from impervious surfaces that is in excess of natural flows otherwise generated from an undeveloped catchment. However, current methods for determining water availability from impervious surface runoff does not account for all the effects of urbanisation on the catchment. This case study has shown that despite a long period of increasing population and associated urbanisation and impervious areas, there has in fact been a reduction in flow to the receiving river downstream of the city of Ballarat.

To monitor the accrued benefits of IUWM, a city's water balance and its assessment must consider flows within downstream waterways. If the system water balance is not completed in this way, multiple effects of urbanisation and the incremental impacts from IUWM such as decentralised systems, changes in land use on the peri-urban fringe and the effect of groundwater from reduced infiltration will not be accounted for. Managing the total water cycle has multiple benefits, but unless it is measured and managed in such a way as to account for all the known impacts, the risk is that unintended consequences may result from well intentioned actions.

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