Key insights from development of policies for integrated water cycle management that include stormwater in Systems Frameworks for Big Data analysis

Dr Peter J Coombes*[1,2] and Dr Michael Barry [3]
Presenting Author

This paper discusses key insights from initiation of water cycle reform and policy development for new thinking about water cycle management across many jurisdictions during the last decade. These successful reform programs were activated in the jurisdictions of the New South Wales, Victorian and Australian Capital Territory governments. Systems Frameworks for Big Data analysis are presented as a powerful process for framing evidence based policy from the "bottom up" using all available data and integrating all available spatial and temporal scales of behavior. The often overlooked (in favour of discussions about harvesting) integration of soil profiles, vegetation, land uses and waterways in the System Framework policy process is explained. It is a key insight that waterways, land uses and stormwater management are inexorably linked to water cycle and town planning systems and are the foundations of successful water cycle management. The value of waterway and stormwater management policies and actions are only fully realised from a systems perspective. The Systems Framework analysis of biophysical systems reveals that the behaviors of water cycle systems are cumulative rather than static. This insight indicates the potential exponential impacts of missed opportunities and a need for ongoing diligence to avoid transferring substantial problems to future generations.

I. Introduction

This paper discusses insights from the initiation of water cycle reform and development of policies for new thinking about managing water cycle systems across many jurisdictions during the last decade. These successful reform programs were informed by systems analysis and activated in jurisdictions of the New South Wales, Victoria and the Australian Capital Territory governments. The development of Systems Frameworks of Big Data by the first author has evolved over the last two decades of continuous applied research within a science and policy domain. This paper also presents some of the key influences on the development of Systems Frameworks of Big Data, the power of systems analysis to frame evidence based policy and presents key systems insights relating to stormwater management from recent analysis. This applied research journey originates with and includes major scientific contributions that commenced in the 1960s as summarised below.

The earth functions as an interactive system and humans influence the physical characteristics of this system. The Gaia Hypothesis proposed, in the 1960s, that our planet is a single, albeit complex, organism that maintains a

[1] Urban Water Cycle Solutions, Albert Park Victoria, thecoombes@bigpond.com
[2] Chief Scientist at Office of Living Victoria, Melbourne Victoria, peter.coombes@olv.vic.gov.au
[3] BMT WBM, Brisbane Queensland, michael.barry@bmtwbm.com.au

homeostatic or balanced state (Lovelock, 1979). This has been defined as a complex system that includes the earth's biosphere, atmosphere, oceans and soil profiles in a feedback or cybernetic system. However, the strength and resilience of natural systems is challenged by human intervention as a function of the connectedness of all things (including human behavior) in nature (Carson, 1962). Our Earth system is vulnerable to the unforeseen cumulative impacts of exponential growth of human settlements dependent on ecosystems services or natural resources (Carson, 1962; Meadows et al., 1972). Earth systems are also challenged by human impacts on climate processes (Arrhenius, 1896; Callendar 1938; IPCC; 2014). These impacts are a challenge to the stability of ecological and economic systems.

Urban settlements are located in the biosphere and are dependent on ecosystem and climate processes. The productive area required to support current consumption patterns associated with prevailing economic and technical processes was proposed as an Ecological Footprint by Wackernagal (1994). It is estimated that Australia has an ecological footprint of 6.6 global hectares per person (WWF, 2012) which indicates high rates of greenhouse gas emissions and potential degradation of biodiversity, soil and waterways.

Although environmental issues are often excluded from economic decision making as externalities, the services that ecological systems contribute to human welfare, both directly and indirectly represent substantial economic value (Constanza et al., 1997). Indeed it was proposed, in 1997, that the minimum value of the Earth's ecosystem services was an average of US$33 trillion per year which was a stark comparison to the total global gross national product of around US$18 trillion per year. The viability of ecosystems is also challenged by increasingly temperature driven variability of climate processes (IPCC, 2014).

Systems' thinking is an approach to understanding challenges and opportunities within an overall system rather than reacting to problems in isolation to an overall system which may produce unintended or unforeseen consequences. Systems analysis of the timelines of growth and associated behaviours of a city allows understanding of the dynamics of urban settlements (Forrester, 1969). These frameworks of urban systems provide understand of the potential impacts of intervention policies on urban futures. However, these processes can be included as sub-systems in analysis of the dynamics of world systems (Forrester, 1971). This allowed the Club of Rome, in 1972, to examine the long term drivers and impacts of population growth, industrial capital, food production, resource consumption and pollution on the future state of the Earth (Meadows et al., 1972).

Systems analysis is a framework of approaches and habits that is based on the behavior of component parts of a system that are revealed by the context of relationships with other components of the system (Forrester, 1969; Meadows et al., 1992; Kuczera and Coombes, 2001). A systems analysis understands the linked, cumulative and cyclical nature of systems in response to distributed behaviours rather than the relying on linear and static assumptions about parts of a system (Coombes, 2002).This is a contrast to the scientific reductionism or deterministic and singular discipline approach to analysis and design which often underpins professional practice. Systems analysis frameworks consider the linkages and interactions between elements that comprise an entire system.

A society (a market) is a system that involves multiple transactions or decisions (behaviors) that occur at multiple scales. The economic behavior of society is traditionally approximated using simplified supply and demand processes based on whole of system approximations (Coombes, 2014). However these processes cannot replicate the multiple dependent transactions throughout a system (for example with respect to intersection of a water cycle with town planning processes) – and, therefore, cannot understand or value a system that changes from the smallest distributed scales (from the bottom up) in response to the choices of people in the system.

Game theory relating to non-competitive games and the Nash Equilibrium allows achievable solutions to the optimization of multiple transactions or behaviors throughout a system. The Nash Equilibrium is based on the concept of best response where each player in a game selects the best response to the other players' known best strategies (Nash, 1950a; Nash 1950b). Thus the Nash Equilibrium can be used to approximate optimum behaviors or decisions in responses to multiple drivers (such as selection of water efficient appliances) throughout a distributed system.

Research into "Big Data" emerged from computer sciences and systems research in the 1970s (Halievi and Moed, 2012). There has been a substantial increase in publications referring to Big Data since 2008. Big data Analysis is the term for a collection of large and complex datasets that are difficult to process or understand using traditional database management tools or data processing applications (Coombes and Barry, 2014).

Development of evidence based policy has garnered substantial interest throughout a range of policy development domains. However, a barrier to the process of developing or implementing evidence based policies can be perceptions of certainty or uncertainty about data or information from a typically single, partial or limited sources. In contrast, a Systems Framework includes and links multiple layers of temporal and spatial data or information from many different disciplines and from multiple perspectives. Systems Frameworks link and process information across time and space, that include Big Data analysis processes and respond to external drivers such as variations in climate thereby limiting the uncertainty associated with analysis using deterministic or reductionist methods. These key ideas were the drivers for development of a systems analysis that is built on local scale (the people) inputs (a "bottom up" process) rather than traditional analysis of metropolitan water resources that commences with regional scale assumptions (a "top down" process). This process using Big Data within a Systems Framework has revealed a range of challenges and opportunities for water cycle management in Australia that were hitherto obscured by more generalised analysis techniques.

II. Key systems concepts relating to stormwater management

The forensic analysis of inputs to the Systems Framework and ultimate analysis across many projects has provided key insights into stormwater management and impacts on waterways. The dynamics of stormwater management is dependent on many interacting elements of the water cycle and urban development. The traditional definition of stormwater catchments and solutions is shown in Figure 1 and the definition of integrated catchments and solutions used in the Systems Framework is presented in Figure 2.

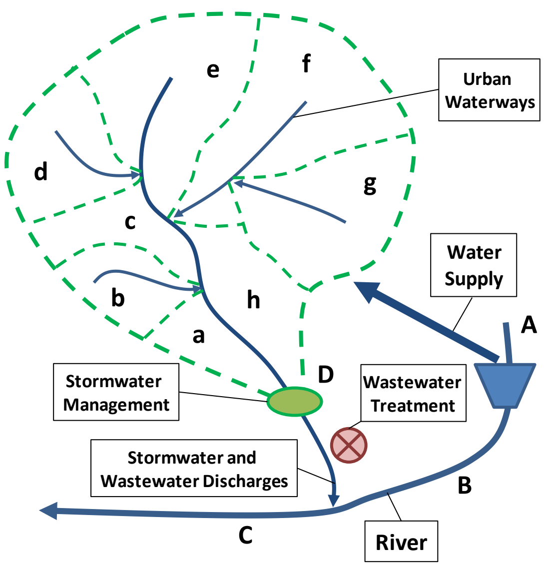

Figure 1: Traditional definition of stormwater catchments for centralized solutions

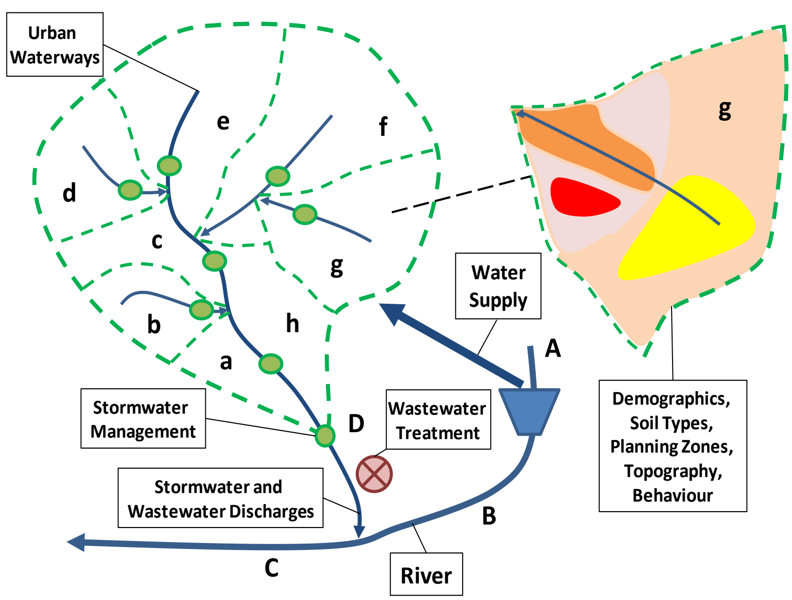

Figure 2: Definition of catchments and land uses for integrated spatial solutions

Figure 1 presents a regional scale system and shows the different responses within a river basin and a linked urban catchment. The impervious surfaces and hydraulically efficient infrastructure associated with urban catchments increases the magnitude and frequency of stormwater runoff whilst reducing the infiltration to soil profiles and subsequent baseflows in waterways (Coombes, 2002; Walsh et al., 2012). The first response at A is the (undisturbed) ecosystem upstream from urban impacts, the second response at B includes the impact of water extraction to supply the urban area (changed flow regime from water supply) and the third response at C includes water discharges from the urban catchment (changed flow and water quality regime from both stormwater runoff and wastewater discharges) into the river basin. Clearly analysis and solutions at point D as "end of pipe" management also excludes understanding of impacts within the urban catchment (sub-catchments a-h) and external impacts to the river basin at B and C.

Traditional analysis of the performance of the urban catchment is from the perspective of management at the bottom of the urban catchment (D) using retarding basins, constructed wetlands and stormwater harvesting. However, the benefits for flood protection, improved stormwater quality and protection of the health of waterways from this approach do not occur within the urban catchment upstream of point D. Indeed, traditional stormwater management practice require minor and major conveyance methods where the minor approach is a pipe and inlet pit drainage network provided for a given rainfall frequency (for example a 10 year average recurrence interval[ARI]) and the major approach to management conveys excess stormwater runoff along road profiles and overland flow paths (Engineers Australia, 2009).

This reductionist design approach embedded in Australian practice presents a range of challenges that are associated with the increasing accumulation of stormwater runoff towards the outlet of an urban catchment, a design assumption that peak rainfall creates peak stormwater runoff, changing urban form and diminished capacity of conveyance infrastructure. The acceptable design accumulation and concentration of stormwater runoff in pipe systems and road profiles also increases the risk profile of these networks as stormwater travels downstream. Increasing urban density (Barton et al., 2007), diminished capacity of drainage infrastructure (Coombes et al, 2002), blocked inlet pits to the pipe network and the changed characteristics of rainfall runoff responses (peak stormwater runoff is not created by peak rainfall) generate the potential for unexpected impacts within urban catchment with traditional drainage networks and bottom of the catchment solutions.

In addition, real sequences of rain events deliver a wide range of runoff volumes at variable timing that is not captured by current design storm assumptions that produce fixed volumes and timing, or rational method assumptions that also do not incorporate volumes or time (Kuczera and Coombes, 2002). Systems Framework processes (that include continuous simulation and multiple sequences of equally likely rainfall and runoff timelines) allow understanding that the volume and timing of stormwater runoff is highly variable and the determination of the probability of stormwater responses – thus critical stormwater peak discharges commonly used in design are highly sensitive to variations in the biophysical (including town planning) and climate systems.

However, there are many ecosystem and biophysical responses within the urban catchment. Figure 2 shows that the behavior of the urban catchment is analysed in the Systems Framework at multiple linked scales including regional, urban catchment and distributed scale sub-catchments that contain local scale information. The local scale drivers of behavior of the urban systems include demographics, soil profiles, planning zones, topography, vegetation, human behavior and urban infrastructure. In addition, the systems analysis includes changed impacts on surrounding areas that can result from local stormwater scale management by using excess stormwater generated by urban surfaces to supplement water supplies, utilizing vegetation and retaining stormwater in the soil profile. The impacts of these local approaches such as improved urban amenity, increased liveability and decreased urban heat island effects are integrated into the biophysical system.

The detailed structure of the urban catchment used in the Systems Framework reveals that the responses of the urban catchment are cumulative rather than static or average and are dependent on spatial and temporal characteristics of the system. This insight shows that the impact of hidden or missed challenges within catchments will not be linear processes and may be exponential in nature. Whilst traditional "end of pipe" analysis may indicate limited benefits or impacts of actions within catchments, the actual behaviors within catchments can produce substantial benefits or impacts.

Analyses that is limited to stormwater management (both ecological and infrastructure related) at the "end of pipe" scale are unlikely to account for the true complexity of the urban catchment and provides only "net effect" information. This type of information cannot be deconstructed to the necessary detail to provide information about waterway processes and usually precludes the effectiveness of decentralized or within catchment solutions. How can decisions about integrated water cycle management (or whole of water cycle management) be made if there is only non-responsive data from traditional analysis to infer decisions from? The rush to solutions fosters the oversimplification of such notions as integrated water cycle management or whole of water cycle management, and favors the tendency to ignore the complexity of natural and human systems.

In addition, the Systems Framework links actions at any scale or location within the entire system. For example, stormwater runoff generates peak discharges and surcharges in wastewater infrastructure; and harvesting rainwater and stormwater can reduce impacts on waterways including flooding, stormwater pollution, erosion and flow regimes. Cumulative actions at the smallest scale, such as retaining stormwater in the soil profile can produce significant responses throughout urban systems and to surrounding systems. Changing land uses within an urban catchment has the potential to change the regimes of stormwater runoff volumes and quality throughout an urban catchment and in surrounding river basins. The impact of traditional evaluation of stormwater management upstream of location D (Figure 1) is shown in Figure 3 and analysis of stormwater management using the Systems Framework approach (Figure 2) is presented in Figure 4.

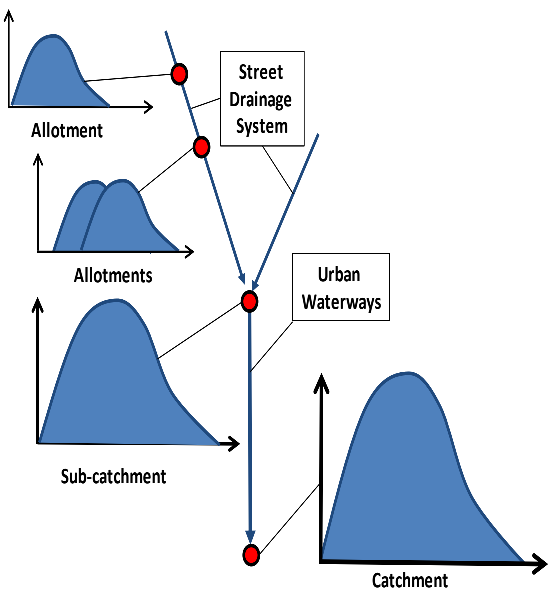

Figure 3: Traditional evaluation of stormwater management at end of pipe

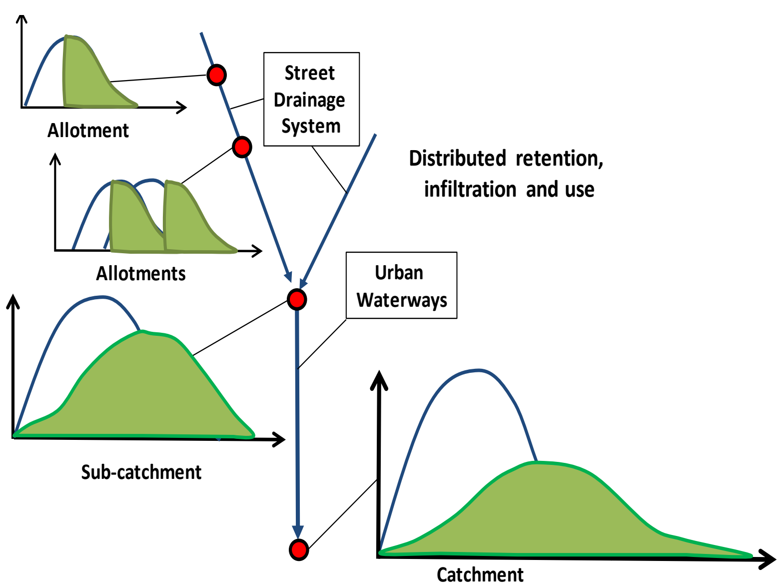

Figure 4: Integrated evaluation of stormwater management in the Systems Framework consistent with natural processes

Figure 3 shows traditional stormwater management where individual land uses (allotments) produce hydrographs of stormwater runoff to the street drainage system. The street drainage system accumulates stormwater runoff from multiple inputs that creates progressively larger volumes of stormwater runoff that ultimately flows into urban waterways. This process results in dramatic changes in the volume and timing of stormwater runoff in urban waterways.

Figure 4 demonstrates that impacts of distributed stormwater retention (for example; retaining stormwater in the soil profile to maintain soil moisture, landscaping and vegetation, and rainwater harvesting) throughout urban catchments that can be understood using Systems Frameworks. Continuous simulation, multiple climate sequences and linked processes across the entire water cycle (including water demands) allows understanding of the retention status and the probability of responses throughout the urban catchment.

Even if it is assumed that a distributed retention strategy does not reduce peak discharges from individual land uses discharging to the drainage systems, the reduced volumes and timing of stormwater runoff inputs changes the characteristics of accumulated stormwater runoff as stormwater travels downstream. This example shows the significance of stormwater management interventions within the headwaters of catchments.

III. Key systems insights relating to stormwater from policy processes

The different policy development processes for Sydney, Melbourne, the Australian Capital Territory and regional Victoria generated a range of key insights arising from integrated systems analysis. Ongoing development of a Systems Framework has included the entire water cycle, environmental and big data processes to frame evidence based policy using all available data. Integrating all of the spatial and temporal scales of behavior in the Framework has allowed a detailed understanding of trade-offs in benefits and costs throughout society.

Part of the genesis of the Living Victoria policy (Coombes and Bonacci Water, 2012) and Melbourne's Water Future (OLV, 2013) strategy was evidence submitted by Coombes, (2009) to the Victorian enquiry into Melbourne's Future Water Supply that was motivated by the recent drought. The Living Victoria process resulted in historical water cycle reforms for the Greater Melbourne region. The systems analysis underpinning the policy revealed that the increasing accumulation of stormwater and wastewater throughout expanding and aging water cycle networks is a substantial physical and economic challenge or opportunity for governments. Similar results were found for all jurisdictions.

Population growth drives the dynamic links between water cycle and town planning systems to present strong challenges and opportunities. A variable climate and potential for increased rates of climate change is an additional challenge that will force greater variability of behaviors with associated uncertainty about urban futures. Almost all inputs that describe the performance of urban settlements are subject to strong spatial and temporal variability which drives spatially variable responses to policy measures. A combination of spatially variable responses and non-linear translation of behaviors across scales also reveals opportunities and challenges that are not apparent in average reductionist assessments. Systems analysis has revealed "hidden" opportunities.

The rate of urban development and associated town planning processes are a serious challenge in all jurisdictions for flooding, the health of waterways, urban amenity and the liveability of urban settlements. A rush to solutions that maximize land yield for each new development whilst stormwater management is moved increasingly downstream of urban areas is an exponential driver of substantial future problems. These processes defer increasing cumulative costs and declining liveability to future generations and governments.

Stormwater inflows to wastewater networks drive the design, management and regulatory costs of wastewater infrastructure. Indeed, about 10% to 30% of current and future wastewater capital and operating costs were attributed to stormwater runoff. In addition, the risks of flooding of existing urban areas are substantial and increasing as a consequence of increased urban density, aging infrastructure and management at the "end of pipe". The value of stormwater infrastructure and the costs of stormwater management are a significant proportion of total water cycle values and costs for an urban area. The future volumes of stormwater runoff with associated costs are seen to increase for urban settlements in all jurisdictions as a response to population growth.

Stormwater management strategies also need to focus on the changing characteristics of urban catchments upstream of traditional management approaches. There is a pressing requirement to retain stormwater within the drying urban soil profiles beneath our cities to maintain the health of urban vegetation and to restore base flow in urban waterways which will improve amenity and liveability outcomes. Simply put, our remnant urban vegetation, forests and waterways may not survive ongoing urbanization unless stormwater management practices emerge to meet the challenges.

Population growth also increases the volumes of stormwater and wastewater that are discharged to waterways. Substantial future increases in the loads of pollutants accumulating in waterways and bays are expected for all jurisdictions. These impacts are even higher for inland areas such as the Australian Capital Territory and regional Victoria where waterways are subject to declining fresh water flows and increasing pollutant loads.

Thus the systems analysis has also revealed that alternative water cycle management strategies provide substantial opportunities to mitigate emerging challenges to urban settlements in all jurisdictions. The Systems Framework process includes trade-offs across society and counts all available costs and benefits – stormwater management is a significant cost and water cycle alternatives can provide substantial benefits. The entire system displays accumulative and volume sensitive behaviors. It will be important to implement volume based targets (not just harvesting) for stormwater management and to minimize transfer distances for water, wastewater and stormwater.

Urban catchments that include impervious services are substantially more efficient than water supply catchments in translating rainfall into runoff as previously outlined by Coombes and Barry (2007). However, systems analysis further reveals linked whole of system benefits of rainwater and stormwater harvesting. Rainwater or stormwater is harvesting in urban areas which allows regional reservoirs to fill. This additional "banked" water in reservoirs is utilized during periods of lower rainfall in urban areas. However, rainwater and stormwater harvesting, and vegetated measures within urban areas also reduce the volumes of stormwater runoff with associated pollutant loads. This mitigates flood risks as previously demonstrated by Coombes et al. (2003), the regimes of stormwater flows in urban waterways and risks of wastewater surcharges. Similarly, a policy of increased water efficiency in buildings reduces wastewater discharges and decreases pollutant loads to waterways.

IV. Conclusion

A Systems Framework for Big Data analysis was built on pioneering systems investigations of policies for economic development that commenced with Urban Dynamics, Earth Dynamics and Limits to Growth. The systems philosophy was expanded to also further incorporate the resilience and connectedness of natural systems that are challenged by human behavior and climate processes. Ultimately, the integrated Systems Framework also incorporated the entire water cycle, environmental and big data processes to frame evidence based policy from the "bottom up" using all available data and integrating all the spatial and temporal scales of behavior.

The authors have utilized the Systems Framework to initiate and investigate development of policy for new thinking about water cycle management and reform across many jurisdictions during the last decade. These successful reform programs in the jurisdictions of the New South Wales, Victorian and Australian Capital Territory governments have yielded a range of key insights.

Importantly, the often overlooked (in favour of discussions about harvesting) integration of soil profiles, vegetation, land uses, town planning, water cycle infrastructure and waterways was captured by System Framework which allows greater understanding of the trade-offs and benefits throughout the water cycle, environment and society. It is a key insight that waterways, land uses and stormwater management are inexorably linked to water cycle systems and are the foundations of successful water cycle management. The value of waterway and stormwater management policies and actions are only fully realised from a systems perspective. Moreover, the Systems Framework analysis of an entire biophysical system (total water cycle management) reveals that the behavior of water cycle systems is cumulative rather than static. This insight indicates the potential future exponential impacts of missed opportunities that may be otherwise "hidden" by traditional or reductionist approaches to planning and design of human settlements with associated infrastructure. This insight indicates need for ongoing diligence and innovation to avoid transferring problems to future generations.

References

Arrhenius S., (1896). On the influence of carbolic acid in the air upon the temperature of the ground. Philosophical Magazine. 41, 237-276.

Barton A. F., Coombes P. J., and Sharma A., (2007) Impacts of innovative WSUD intervention strategies on infrastructure deterioration and evolving urban form, Rainwater and Urban Design Conference 2007, Sydney. Australia.

Callendar G.S., (1938). The artificial production of carbon dioxide and its influence on climate. Quarterly Journal of Meteorological Society. 64, 223-240.

Carson R., (1962). Silent Spring. Houghton Mifflin. Massachusetts. USA

Coombes P.J., and Barry M.E., (2014). A systems framework of big data driving policy making – Melbourne's Water Future. OzWater2014 Conference. Australian Water Association. Brisbane Australia.

Coombes P.J., (2014). Towards frameworks for systems economics. http://urbanwatercyclesolutions.com/systemseconomics

Coombes P.J., (2013). 14 Key principles for water cycle policy. Water. Journal of the Australian Water Association. September, 8-9.

Coombes P.J., and Bonacci Water (2012). Living Melbourne, Living Victoria. Greater Melbourne systems model – modelling in support of the Living Victoria Ministerial Advisory Council.

Coombes P.J., (2009). Evidence to inquiry into Melbourne's future water supply. Environment and Natural Resource Committee. Hansard of the Victorian Parliament.

Coombes P. J., and Barry M. E., (2008). The relative efficiency of water supply catchments and rainwater tanks in cities subject to variable climate and the potential for climate change. Australian Journal of Water Resources, 12 85-100.

Coombes P. J., Kuczera G. A., Frost A. J., O'Loughlin G., and Lees S., (2003). The Impact Of Rainwater Tanks In The Upper Parramatta River Catchment', Australian Journal Of Water Resources, Vol. 7 121-129.

Coombes P.J. (2002). Rainwater tanks revisited. New opportunities for integrated water cycle management. PhD Thesis, School of Civil and Environmental Engineering. University of Newcastle. Australia. Available at http://urbanwatercyclesolutions.com

Coombes P. J., Micevski T., and Kuczera G. A., (2002). Deterioration, Depreciation And Serviceability Of Stormwater Pipes. Exploding the Myths: Stormwater Driving The Water Cycle Balance, Orange, New South Wales.

Costanza, R., d'Arge R., deGroot R., Farber S., Grasso M., Hannon B, Limburg K., Naeem S., O'Neill R. V., Paruelo J., Raskin R. G., Sutton P., and van den Belt M., (1997). The value of the world's ecosystem services and natural capital. Nature. 387, 253-260.

Engineers Australia, (2009). Australian rainfall and runoff. Book 9: Runoff in urban areas.

Forrestor J.W., (1969). Urban Dynamics. Massachusetts Institute of Technology Press. Cambridge, Massachusetts, USA.

Forrester J.W., (1971). World Dynamics. Wright-Allen Press. Cambridge. USA

Halievi G., and Moed H., (2012). Big Data: science metrics and the black box of science policy. Research Trends. 30, 3-6.

IPCC., (2014). Climate change 2013: the physical science basis. Fifth assessment report of the Intergovernmental Panel on Climate Change.

Kuczera G. A, and Coombes P. J., (2001). A Systems Perspective of the Urban Water Cycle: New Insights, New Opportunities, Proceedings of the 5th Regional Conference on Urban Stormwater Management, Port Stephens, NSW.

Kuczera G.A., and Coombes P.J., (2002). Towards Continuous Simulation: A Comparative Assessment Of Flood Performance Of Volume-Sensitive Systems, Exploding The Myths: Stormwater Driving The Water Cycle Balance, Orange, New South Wales

Lovelock J.E., (1979). Gaia: a new look at life on Earth. Oxford University Press.

Meadows D.H., Meadows D.L., and Randers J., (1992). Beyond the limits. Global collapse or a sustainable future. Earthscan Publications. London. UK.

Meadows D.H., Meadows D.L., Randers J., and Behrens W., (1972). Limits to growth. Universe Books. New York.

Nash J.F., (1950a). Equilibrium points in n-person games. Proceedings of the National Academy of Sciences. USA. 36, 48-49.

Nash J.F., (1950b). The bargaining problem. Econometrica. 18, 155-162.

OLV (2013). Melbourne's water future. Consultation draft. Office of Living Victoria.

Wackernagel, M. (1994), Ecological Footprint and Appropriated Carrying Capacity: A Tool for Planning Toward Sustainability. Ph.D. Thesis, School of Community and Regional Planning. The University of British Columbia. Vancouver, Canada.

Walsh C.J., Fletcher T.D., and Burns M.J., (2012). Urban stormwater runoff: a new class of environmental flow problem. PLos ONE 7(9), e45814. Doi:10.1371/journal.pone.0045814.