Modifying the Green Roof for Downunder

Authors

Mark Liebman, The Sustainability Workshop, mark@sustsainabilityworkshop.com

Laith Wark, Verdaus Landscape Architecture, laith@verdaus.com

Craig Mackay, Enstruct, craig.mackay@enstruct.com

Abstract

We explore the feasibility of constructing an urban farm on top of an industrial distribution centre. The "rooftop urban farm" would need to be irrigated and this would occur by harvesting water from part of the roof and using it to irrigate the remaining part which is "green". This might help to significantly reduce the frequency and volume of runoff from large roofs which are otherwise an intractable problem. Modern distribution centres produce little and so consume little water. Because the demand for stormwater is low harvesting runoff has a negligible impact on reducing discharges. Work by Ladson et al (2004) has shown that directly connecting impervious areas reduces creek health. This is worst when considering the impacts of industrial estates. Ironically Australian cities experience simultaneous water shortages.

If feasible this approach could protect receiving waters by reducing the frequency of runoff, reduce food miles at a time when fringing market gardeners are being pushed out of cities, generate employment, reduce water demand in water stressed regions, as well as reduce heat islands and greenhouse gases. Such an approach, if feasible, would enable green roofs to be sustained in the "dry" Australian climate.

Introduction

In the last 15 years stormwater policy in Australia has evolved considerably and continues to do so. Water quality discharge standards vary across Council and State boundaries (Liebman et al, 2009). Until now the focus of these treatment measures has been to improve the chemical quality of stormwater discharged from the site. Underpinned by research by Wright et al (1999) and Ladson et al (2004) and more recent policies such as the Stormwater to Smartwater policy (CWCMA, 2011) developed for the Central West CMA, there is a trend toward controlling not the water chemistry but the volume and frequency of runoff. Such policies can be applied without too much difficulty or cost to development on residential land but to date make no sincere attempt to control runoff from industrial land. Volume and frequency controls are unable to be applied to modern industrial buildings which have roof areas often exceeding ten hectares and where just 1mm of runoff will yield 100,000 litres of stormwater. The reason for this is simply because there is almost no chance of complying with such a requirement. For example, if 50mm of rain falls you then need to dispose of 5ML of water on a clay based site where infiltration is typically limited to one or two mm/hour – areas available for infiltration are also limited because the value of land is high. You can only flush limited volumes of water down the toilet leaving no other obvious disposal options. In this context we talk about "disposing" of stormwater because it has no apparent value and as a waste product it causes significant environmental problems. Knowing that Sydney suffers from water scarcity and that water is a scarce resource should suggest that there is not "too much" stormwater there is instead a shortage of demand. Runoff here needs to be viewed as a problem of scarcity not a problem of abundance.

Wyong Council on the NSW central coast has been charged with facilitating the development of Warnervale and Wadalba in a sustainable manner. Porters Creek Wetland which drains Warnervale and Wadalba must be protected from an increase in the frequency and volume of runoff (Ecological Engineering, 2007) and be permitted to dry out and flood appropriately. As a result, Council and its consultants have developed a centralised approach which would pump stormwater so that it bypasses Porters Creek and instead is conveyed down the tidal Wyong river to the sea. This centralised approach works in this coastal context where there is a less sensitive tidal receiving water. The upfront capital costs of such a scheme have thus far been prohibitive and the viability of the project is dependent on grant funding from either the Federal or State Government and then unpredictable developer contributions to fund the remainder of the works.

The work by Ladson et al (2004) has shown how creek ecological health declines when there is an increase in the connected impervious area. Furthering Ladson et al's (2004) work, the Little Stringy Bark Creek team (http://www.urbanstreams.unimelb.edu.au/) is focussed on reducing runoff frequency and volume from a residential development which typically has an imperviousness of 40% to 50%.

This paper builds on the previous body of work and explores if it is feasible to reduce runoff volume and frequency from large industrial developments characterised by 95% directly connected areas using a decentralised approach not dependent on grant funding for key infrastructure but instead developer funded.

Modern town planning and low cost transport has resulted in retailers developing distribution hubs serviced by large distribution centres. As a result a number of large distribution centres are being built across Australia. We focus in particular on the construction of a distribution centre by a large food retailer in western Sydney. The centre is located on 12 hectares of land and has an eight hectare roof. We have examined the feasibility of constructing a rooftop urban farm which is to be irrigated with water harvested from the roof.

We used a water balance to:

1) Estimate how much we could reduce runoff frequency and volume.
2) To optimise how much roof was to be dedicated to farming and how much of the roof would be left over to shed water so that it could be stored and used to irrigate the green part of the roof.
3) To optimise the size of rainwater storage tanks needed to sustain such a farm.

We worked with structural engineers, Enstruct, to redesign such a warehouse and estimate how much more steel is required in the structure, while ensuring the warehouse would operate normally and how this will impact on construction costs. We have estimated the value of food that could be harvested from the roof and developed a life cycle cost to assess the viability of this proposal. We have also estimated the green house gases that could be reduced by reducing food miles.

This feasibility study must be understood in terms of the significant economic pressure to develop every square metre of commercial land. Because of the pressure to develop it is not possible to have large on-ground areas devoted to irrigation or infiltration. Typically a loss of developable area of 2% to 3% for stormwater treatment is barely acceptable.

Methodology

Description of the proposal

This feasibility study focussed on a typical distribution centre with an 8 Ha roof area. The dimensions of the roof are 200m wide X 400 m long as shown in Figure 1 below:

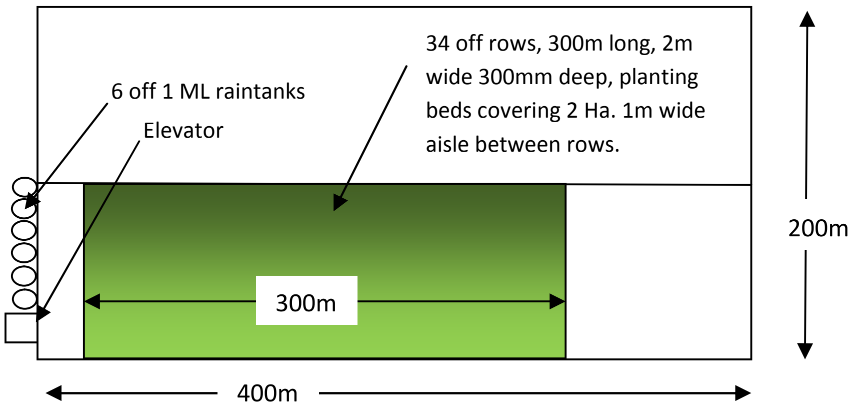

Figure 1 Sketch showing a plan view of the 8 Ha distribution centre (not to scale)

An optimised solution is shown in Figure 1 noting that the optimisation process is explained in more detail below. The water storage tanks were assumed to be 1 ML each, 5 m high which leaves about 4m of elevation head difference between the gutters on a 9 m high roof and the top of the tanks.

The growing media would be comprised of a lightweight loam with an optimised organic content. Optimisation here means minimising site runoff while maximising food produce. A good starting point for growing media design would be the FAWB Bioretention Guidelines (FAWB, 2009).

The beds would be 300 mm deep which would permit the soil to be mounded in rows to a greater height for crops such as potatoes or leeks or to remain at 300 mm for shallow rooting crops such as lettuce, herbs and the brassica family.

The beds would be lined with a low porosity non-woven geotextile to prevent the migration of soil particles out of the beds. The beds would be underlain by a shallow drainage cell with a water proof membrane below that. Roof material would be constructed from an engineered plywood which is both non-yielding and able to absorb impacts from the work above.

We assumed an elevator would be needed to move produce down and equipment, seeds and seedlings up. We also envisaged that a motorised travelling gantry, located on rails in the aisle between beds would enable automatic sowing and easy hand harvesting. It would allow the 300m long beds to be travelled rapidly without exhausting labour. Our concept allows for the gantry to span across 5 beds and be supported each end by a beam.

To avoid the need to carry compost up onto the roof a system called fertigation would simultaneously water the rooftop beds and apply liquid nutrients and trace minerals to maintain soil productivity. Automatic irrigation would be established on the roof within each bed to ensure a highly efficient irrigation process.

One of the problems of urban rooftop farming is the potential leaching of soluble nutrients from the shallow soil during rainfall events. This may occur on this site however leached nutrients would be collected and returned to the green roof provided that tanks were not overflowing. If required overflows from the storage tanks could be treated in a bioretention basin allowing the water to percolate through a filter media column delivering water quality suitable to meet any discharge requirements.

Water balance methods

We used a water balance to:

1) Estimate how much we could reduce runoff frequency and volume.
2) To optimise how much roof was to be dedicated to farming and how much of the roof would be left over to shed water.
3) To optimise the size of rainwater storage tanks needed to sustain such a farm.

We used both the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) and a Microsoft Excel spreadsheet to model the water balance. We estimated irrigation demand to be the deficit between Evapotranspiration and rainfall noting that, for most common vegetables, a crop coefficient of 1 is suitable (FAO, 1998). We assumed an irrigation efficiency of 85% using drip lines and drip feeders. We also assumed a rainfall effectiveness of 0.65 though this has little impact on total demand.

Climate data for the water balance was obtained from the Bureau of Meteorology. Daily rainfall from Prospect Reservoir (station number 67019) from 1887 to 2012 was used. This was matched with monthly areal potential evapotranspiration from Parramatta. The annual average irrigation demand was estimated to be 1144 mm/year with average rainfall of 867 mm/year and evapotranspiration of 1171 mm/year.

A MUSIC model was then set up with 2 source nodes. One source node represented the irrigated green roof part of the roof and the other source node represented the normal part of the roof which was used to harvest water.

In order to more accurately model the runoff regime from the irrigated green roof source node in MUSIC the following method was adopted:

1) Created a 1 Ha one node model which was later scaled to 2 and 3 hectares simply by copying it. The 1 Ha one node model is representative of 1 Ha of green roof with 100% pervious surface. Soil parameters were estimated from the methods described by Macleod (2008).

Soil storage was estimated to be 58 mm. Field capacity was estimated to be 53 mm. The climate file used in this model was an amended rainfall file. It included both rainfall and the irrigation demands modelled earlier in Excel. In other words we were able to model both rainfall and irrigation being applied to the green roof so that we could model the circular water cycle system proposed.

The outflow from this node was then exported with the results reflecting the fact that the shallow soil store was irrigated and this did increase runoff frequency and volume. Standard nodes in MUSIC do not account for any applied irrigation which, in cases like this, can elevate runoff frequency and volume. Given the primary purpose of the green roof is to minimise runoff the more accurate runoff modelling procedure was warranted. Very high levels of reliability of supply meant that it was not necessary to iterate the procedure to refine the results.

2) We constructed another MUSIC model comprised of an "imported" node which contained the exported output from point 1) above and which is shown in Figure 2 as "1 Ha of irrigated roof". This node was simply copied to model 2 Ha of irrigated green roof and copied again to model 3 Ha of irrigated roof and so on. The model also included an impervious node shown in Figure 2 as "imperv roof area". These nodes were directed to a rainwater tank and the results analysed. The rainwater tank volumes were optimised and it was found that 6 ML of storage would provide the optimum volume of reuse needed to sustain the rooftop farm.

3) In order to work out what proportion of the roof area would be needed for green roof or farm and what proportion for harvesting runoff we tested 1 Ha, 2 Ha and then 3 Ha of green roof and did this simply by adding additional 1 Ha irrigated roof nodes and subtracting the extra hectare from the impervious roof area node as shown in Figure 2 which shows the 2 Ha case under investigation and where the "imperv roof area node" is 6 Ha.

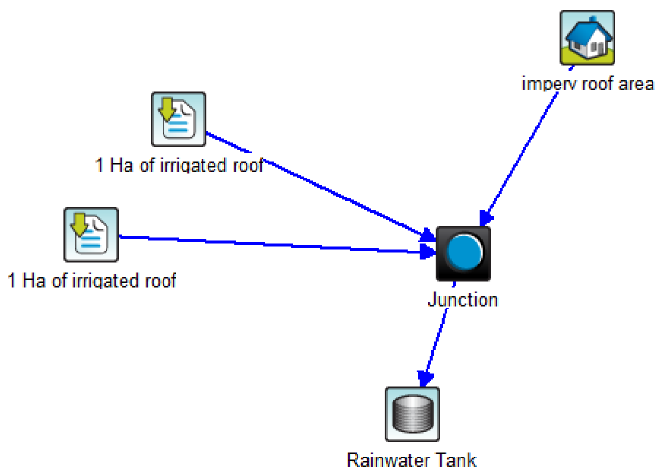

Figure 2 MUSIC model layout showing 2 Ha of irrigated roof with 6 Ha of impervious roof area.

We created a used defined time series to model irrigation demands from the rainwater tank. The time series consisted of the irrigation demands modelled in the Excel spreadsheet.

Structural Calculations

Enstruct undertook the structural calculations for this feasibility study. A first pass examined the feasibility of retrofitting a green roof to an existing distribution centre. It was found that loading of the green roof would have required complete reconstruction of the existing building during the building operation and this was deemed to be unfeasible.

We then examined the case of a new build. Calculations show that column spacings needed to reduce in one direction from 9 m in a normal situation to 6m with a green roof and in the primary direction from 20 m down to 7.5 m. The roof material would be constructed from an engineered plywood with an F22 strength rating instead of the typical clip lock style corrugated iron roof sheets. This would effectively allow a working platform to be created on the roof. Purlin spacing would be halved thus doubling the lineal metres of purlins required.

The rolling rooftop gantry which is used as a moving platform to rapidly and easily work across the 300m long beds was to be supported by a universal beam each end with 15 m spans. Primary steel members were sized to span the 7.5 m column grid. We had allowed 500 kg of materials to be loaded onto each gantry.

We did not allow for any increase in the size of the footings supporting the structure. Typically such large structures are built on large cut and fill earth platforms where compaction of the soil is undertaken in a layered approach. Floors, constructed from post tensioned concrete slabs are normally able to support racking loads which tend to far exceed the building loads even with a green roof. Any extra over costs here are going to be highly site dependent and worthy of further investigation.

Construction & operation costs

Construction and operation costs were estimated using standard engineering estimating techniques. We made the following assumptions regarding pumping costs:

1) Pumps would need to pump 25 m total head (9m elevation head plus 16m velocity head and losses). Drip feeders and drip lines can apply a constant feed of water directly to the plant roots. This would limit the daily maximum irrigation volume and keep peak pump flow rates to about 2 L/s. As a result a 1 kW pump with 60% efficiency would be suitable and a duty and stand by pump arrangement would be needed.
2) We assumed electricity costs about 15 cents/kW h.
3) Pump volume was assumed to be 22.147 ML/annum. We conservatively estimated a 1kW pump would be required to pump a maximum flow rate of 8m^3/hour to meet a maximum modelled daily demand of 65 m^3/day over an 8 hour irrigation period. To pump 22.147 ML/annum requires 2,768 pump hours per annum and at 15c/kW h pumping electrical costs are relatively minor at $415/annum.

We made the following assumptions for the tanks:

1) Tanks would be constructed above ground on purpose-built foundations with edge beams and of 1 ML size each.

We assumed the waterproof membrane would be constructed from HDPE and welded on site.

Steel was assumed to cost $5,800/tonne (Rawlinsons, 2012) and only the extra over cost was included in the calculations.

We assumed two staff would be employed full time at $50/hour to grow the produce and have allowed for half a day per week management time in addition. We also allowed for $10K growing bonuses to incentivise the staff.

Value and volume of food produced

The Australian Bureau of Statistics (2004) found that Australian farms produce about 40 tonnes of vegetables per hectare of land. In 2007-2008 it was estimated that vegetable farms in Australia produced on average 28 tonnes of vegetables per hectare per year (Crooks 2009). We adopted the ABS value on the basis that the rooftop farm would be a highly controlled environment where output is likely to be significantly higher than a less controlled environment. The height above ground is also significant from a pest control perspective with most pests not flying so far above the ground level.

Valuing the potential food or cut flower produce from the roof is a difficult task but we have adopted a reference crop method. That is we have based the revenue estimate on a reference crop of bagged baby green leaves. We have chosen this reference crop specifically because it is a high value crop with high water content. Tasmania grows a large proportion of bagged lettuce and baby greens produce from where it is shipped around Australia. Food miles in this instance are about 1600km from Tasmania to Sydney. The retail price of bagged baby greens in Sydney is currently about $32/kg.

Our cost estimate included $2.20/kg for soaking the greens in water and chlorine and packaging and onward distribution to retailers or restaurant consumers. In other words, the farm would need to function as a wholesaler or ideally sell directly to the occupier of the distribution centre. We assumed we would sell the baby green leaves at wholesale prices of between 30% and 40% of retail prices. The ratio of fresh food wholesale prices to retail prices fluctuate significantly over time but tend to fall between 30% and 40% (Spencer, 2004).

Results

Water Balance

Table 1 shows the water balance results.

Table 1 Rainwater Tank - Water Balance Results.

Option		Flow in (ML/yr)	Flow out (ML/yr)	Runoff frequency (Events/yr)	Reuse requested (ML/yr)	Reuse supplied (ML/yr)	% Reuse Demand Met (%)
8 Ha imperv roof	No green roof	61	61	149	0.00	0.00	0
7 Ha Imperv roof	1 Ha Green Roof	60	47	44	11.30	11.30	100
6 Ha imperv roof	2 Ha Green Roof	58	35	25	22.60	22.15	98
5 Ha imperv roof	3 Ha Green Roof	57	25	21	30.24	33.90	89

Results show all three options are able to supply a high proportion of demand however for commercial growing purposes 89% reliability was deemed too low and 98% deemed acceptable.

In terms of runoff frequency there are marginal benefits to be gained from having 3 Ha roof over a 2 Ha roof. The 1 Ha roof did not appear to contribute significantly to reducing the runoff frequency and on this basis was not chosen for life cycle costing.

Based on the water balance results a 2 Ha roof was chosen for structural assessment and life cycle costing.

Levelised Costs

Levelised costs were calculated for the rainwater harvesting component of this project including irrigation. The method used here conforms to that adopted by the NSW Treasury for assessment of projects. It is based on 30-year project life with discount rates shown below.

Table 2 Annualised and Levelised costs for the harvested water

Interest Rate	4.0%	7.0%	10.0%
Annual Cost $	-77,537	-107,266	-140,572
Annual Cost $/kL Yield	**-$3.50**	**-$4.84**	**-$6.35**
Levelised cost$/kL	**-$3.31**	**-$4.48**	**-$5.74**

The calculations show that when a discount rate of 4% is used the water would cost $3.31/kL. These are generally consistent with other large scale roof harvesting projects. The cost here is driven by the cost of rainwater tanks.

Life Cycle Cost Analysis

We undertook a life cycle cost analysis to determine the economic feasibility. The life cycle costing made numerous assumptions about the operation of the rooftop farm including fertiliser costs, the labour required, the costs of packaging and food distribution. It is to be considered an early feasibility assessment with a more thorough analysis required as part of future research.

Operating costs were estimated as follows:

Description	**$ ex GST**
Staff & management & bonuses	$248,000
Materials, packaging and distribution ($2.20/kg)	$176,000
Fertiliser	$16,000
Pumping - irrigation	$415
Elevator & lighting electricity	$1095
Maintenance	$2,000
Total operating costs	**$443,510**

Life cycle costs were then estimated as follows:

Description	**$'000 ex GST**
Capital expenditure	$6,912
Less value of land otherwise required for treatment	$500
Net Capital expenditure	$6,413
Operating costs	$443
Revenue at $11/kg of produce	$880
Net present value at $11/kg - 4% discount and 30 year life	**$1,135**
Internal Rate of Return over 30 years life	**5.4%**

Table 3 shows the variance of net present value (NPV) and internal rate of return (IRR) with wholesale price.

Table 3 Variance of NPV and IRR with wholesale price

Wholesale Price ($/kg)	$9.50	$10.00	$11.00	$12.00
NPV	-$ 939,781	-$ 248,099	$ 1,135,263	$ 2,518,626
IRR	2.7%	3.7%	5.4%	7.0%

The wholesale price achievable will dictate the profitability of the project. Reducing construction costs by fine tuning the concept will also increase profitability. For example reducing the soil depth to 150 mm may reduce the extra over tonnage of steel required to about 230 tonnes and at $12/kg would yield an NPV of $3.30 million and 8.3% IRR. Reducing the depth of topsoil to 150 mm is likely to be feasible but would require research of the effects of reduced topsoil on crop yields.

Greenhouse Gas Reductions

Gaballa et al (2007), shows the average distance travelled for food items is typically 485 km. In this case Tasmania is a known producer of bagged green lettuce and food miles are over 1500 km. The rooftop would see food miles reduced to an average of 25 km. This would equate to a reduction in carbon emissions associated with only the transport of the food by approximately 27 tonnes per year. This could be larger if the bagged lettuce is flown from Tasmania. Regrettably the extra materials required to construct the rooftop farm, mainly steel, would involve the emission of about 600 tonnes of carbon. It would take over 20 years to become a carbon reducing project though over its life this project would reduce carbon emissions.

Conclusions & Discussions

The capital expenditure estimated to be about $6.9 million for this concept is considerable and may be in the order of 10% of the total building cost. The principal cost items include additional steel at $3 million and rainwater tanks which cost about $1.8 million. This accounts for 70% of the capital cost and it is considered the estimation error on these two items is low. It is possible to reduce the steel costs by reducing the depth of topsoil from 300mm to 150mm. However the life cycle costing is more strongly affected by the wholesale price of the produce than the capital cost and even if the extra tonnage of steel was halved the break even wholesale price of produce would still need to be about $10.50/kg.

It is estimated that the urban rooftop farm can produce about 80 tonnes and at $11/kg this amounts to $880,000 of produce per annum at an operating cost of about 55% of revenue leaving an operating profit of about $350k.

The life cycle cost analysis shows that, to payback the investment and create a positive net present value the produce would need to sell at a wholesale price of about $10.50/kg. If this is possible then this concept may be viable. Therefore this type of approach would only be suitable for high value, high water content, produce where freshness of the product is highly valued. There is anecdotal evidence that rooftop gardens in New York have been able to compete in terms of quality and freshness with products consumed the same day of picking. It is also possible that this type of approach may be suitable for organic growing without the use of pesticides and will help to justify the desirable $12/kg wholesale price.

Types of high value produce would include bagged baby greens, fresh herbs and cut flowers. Bagged baby greens retail for between $25/kg and $32/kg and thus a $12/kg wholesale price is about 40% of retail. This is about the same margin that growers of gourmet tomatoes receive (Spencer, 2004).

The water balance shows that such an approach can have a significant impact on the volume and frequency of runoff, reducing the frequency of runoff from about 150 days per year to about 25 days per year. Whether this reduction in runoff from the roof translates into protection of creek health is unknown at this point. It may be that flows leaving the industrial estates are so large with velocities so high that macro-invertebrates and aquatic fauna stand little chance of inhabiting streams even when runoff frequency is limited to just 25 days per year. The ecological mechanisms of biotic decline need to be better understood.

The water balance also shows that 22.6 ML of water will be saved. That is growing food using roofwater runoff which is otherwise a pollutant will save 22.6 ML of precious river flow from being extracted from a river in Tasmania. This is a double aquatic environmental benefit.

It is clear from this study that it is possible to significantly limit runoff from the very largest industrial buildings though both the costs and benefits can be significant. It also shows that decentralised approaches are possible though they require complex systems to be put in place and these may not actually be cheaper though their product will be of much higher value.

Growing food on rooftops is not a new phenomenon however on this scale this concept is untested. The Ford Motor Company in the Detroit in the US has constructed a large industrial green roof on its new factory however that roof is not farmed – it is a typical green roof. If this concept were to move forward it would need to be underpinned by sound research and development in the form of further desktop analysis followed by field and pilot scale trials. It would also take a multidisciplinary team to adequately research each aspect. We conclude that this concept brings the possibility of significantly reducing the aquatic environmental impacts of large industrial buildings, it creates the opportunity for employment, for reducing green house gases and food miles and it may well do so in an economically profitable manner. On this basis the concept may warrant further research and development.

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