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Joint application of Cost-Utility Analysis and Modern Portfolio Theory to inform decision processes in a changing climate

Marinoni, O.[1] Adkins, P.[2]

[1] *CSIRO Sustainable Ecosystems, 306 Carmody Rd, St Lucia QLD 4067, Australia*

Email: oswald.marinoni@csiro.au

[2] *Swan River Trust, Level 1 Hyatt Centre, 20 Terrace Road, East Perth, PO Box 6740 East Perth, WA 6892*

Abstract: High nutrient loads, which damage ecological assets, are a widespread problem for many Australian river catchments. These negative effects can be mitigated by land use changes and/or intervention measures such as the construction of artificial wetlands and water treatment plants. Usually budget constraints limit the number of measures that can be implemented by the catchment management authority. This creates a selection problem: to maximise the total water quality benefits subject to a budget constraint. Here we present a case study from the Ellen Brook catchment in Perth, Western Australia where cost utility analysis (CUA) and subsequent combinatorial optimisation is applied to determine an optimum portfolio of intervention sites. We furthermore apply modern portfolio theory (MPT) and demonstrate how MPT and CUA can be jointly used to take into account aspects of climate change. We find that the methodologies represent auditable ways to determine a robust project portfolio and help to inform environmental investment decision processes.

Keywords: *Multi-criteria analysis, Climate change, Modern portfolio theory, Optimisation, Risk, River catchment*

1. INTRODUCTION

Many river catchments in Australia suffer from high nutrient loads that can eventually lead to eutrophication, shifts in habitat characteristics and replacement of fish species (FAO 1996) or even fish killings which in turn may cause economic losses and impair the recreational value of a region. Prevention or mitigation of these effects can be achieved by appropriate land-use management practices, soil conservation and/or the establishment of riparian and other buffer zone (Withers and Jarvis, 1998). Alternatively structural controls can be established which might involve construction and installation of bioengineering techniques, sedimentation basins and others (USEPA, 2008). A decision whether or not to put such an intervention measure in place will depend on its technical efficiency, the benefits it can achieve and its cost. If a variety of intervention measures are suggested within a catchment we usually need to account for a budget constraint which implies that not all suggested measures can be realized. This creates a selection problem where a subset of potential interventions sites needs to be selected such that the aggregated benefits are maximised while accounting for a budget constraint. A discussion on the problem of selecting an optimal subset of decision options or projects subject to a constraint is not new and quite generic, especially in financial investment optimisation. However the combined use of multi-criteria analysis (MCA) and subsequent optimisation in a natural resource management context is quite recent (Hajkowicz et al. 2005).

What is not dealt with is to link the results of a MCA with a theory that addresses risk diversification in light of an uncertain future. In this paper we plausibly assume that the efficiency of water management investment decision options are related to the uncertainties included in climate change projections, which imposes a risk on water management investments. As climate change models generally project increases in temperature and/or changes in precipitation severe impacts on overland flows and river flows can be expected. Changes in these flow regimes are of particular interest to water management decision makers (e.g. Swan River Trust, 2007). As climate change is not a phenomenon of the distant future but will affect the lifecycles of many water management assets that are designed and built today, water management investments that are made today should be evaluated in light of projected climate change.

Here we present a case study from the Ellen Brook catchment in Perth, Western Australia where cost utility analysis and subsequent combinatorial optimisation is applied to select a portfolio of waterway health intervention measures subject to a fixed budget constraint. However, in light of climate change, the benefits that are returned by the selected projects are uncertain and this imposes a risk on the investment. We account for these uncertainties by applying modern-portfolio theory (MPT) which has risk and return at its centre (Figge, 2004). MPT has predominantly been applied for decades in the financial sector and economic research. It is less frequently applied in water management with the exception of a few recent efforts (e.g. Wolff 2008, Aerts et al. 2008). It should also be mentioned that there are a variety of other efforts - though not based on MPT - to tackle uncertainty in water management (e.g. Chung et al. 2009, Rosenberg and Lund 2009, Brekke et al. 2009). The authors are aware that the suggested workflow is based on simplifications and assumptions. However our primary objective is to develop a consistent methodology which helps inform investment decision processes in light of an uncertain future.

2. METHODS

2.1. Cost Utility Analysis

A comparison of available economic evaluation frameworks including recommendations on how to select an appropriate method is given in Hajkowicz (2005) who concluded that many natural resources management investment decisions may be solved with cost utility analysis (CUA) or multi-criteria analysis (MCA). Hajkowicz (2005) also provides a review of the history of CUA. CUA as it is used here can be regarded as an extension of MCA: the utility scores of the suggested intervention measures are computed with a MCA and these scores are put in relation to their costs giving the benefit cost ratio BCR. The BCR is a measure that reflects how much benefit is returned for every dollar spent, or in other words, how effectively expenditure is allocated? The costs assigned to the intervention sites evaluated in this paper are discounted lifecycle costs which reflect the value of an intervention site over the lifetime of the asset. To compute the utility scores a multi criteria analysis method called Compromise Programming is used which is a well established method that is frequently used in water management and other NRM contexts (Hajkowicz and Collins 2007). As it is not a new method it is not discussed in any detail in this paper.

2.2. Combinatorial optimisation

Combinatorial optimisation aims to find the combination of intervention sites that return the maximum attainable aggregate utility score (benefit) for a given fixed budget. This problem is an inherently binary decision problem with two possible outcomes for each site: select or not select. The finding of the optimal combination subject to one or more constraints is well known in operations research as the Knapsack Problem (KP) (e.g. Martello et al., 2000, Gomes da Silva et al., 2006). To solve the given combinatorial problem an exact solution method (branch and bound) was used. The imposed budget constraint was AUS$ 1.437 million.

2.3. Modern Portfolio Theory

Modern Portfolio Theory (MPT) was developed in the early 1950's and is primarily based on the work of Markowitz (1952). MPT is routinely applied by financial asset managers who usually are not aiming at investing in a single asset but into a portfolio of assets. While investing into one asset may result in a higher return, it may be considerably riskier. The term risk is used here as it is used in corporate financial terms, namely as the standard deviation of the expected returns. However, assets should not arbitrarily be combined to form a portfolio as in the presence of highly positively correlated assets, asset returns may move up and down together which would be risky. If returns are not correlated, diversification can even eliminate risk (Markowitz, 1959). As mentioned above the expected returns of the individual portfolio assets, their standard deviations and the correlation between the returns of the assets involved are central to portfolio theory. The expected return of an asset R_i (with i = 1..n where n is the number of assets) is given by

$$E(R_i) = \sum_{k=1}^{m} p_k E(R_{ik}) \tag{1}$$

where $E(R_i)$ is the expected return of asset i across a set of given scenarios k (with $k = 1,..,m$), e.g. a set of climate scenarios, p_k is the probability that a scenario k occurs and m is the total number of possible scenarios. $E(R_{ik})$ is the expected return of asset i for a scenario k. The variance of an individual asset's return Var(R_i) is

$$Var(R_i) = \sum_{k=1}^{m} p_k (R_{ik} - E(R_i)) \tag{2}$$

its standard deviation is accordingly

$$\sigma_i = \sqrt{Var(R_i)} \tag{3}$$

The expected return $E(R_p)$ of a portfolio of n assets is

$$E(R_p) = \sum_{i=1}^{n} w_i E(R_i) \tag{4}$$

where w_i is the weighting or the share of asset i within the portfolio p. The portfolio variance or the risk of a portfolio σ_p^2 is given by

$$\sigma_p^2 = \sum_{i=1}^{n} w_i^2 \sigma_i^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} w_i w_j \sigma_i \sigma_j \rho_{ij} \tag{5}$$

where ρ_{ij} is the correlation between two assets i and j. ρ_{ij} is determined by

$$\rho_{ij} = \frac{\sigma_{ij}}{\sigma_i \sigma_j} \tag{6}$$

with σ_{ij} being the covariance between two assets i and j which is computed via

$$\sigma_{ij} = \sum_{k=1}^{m} p_k (E(R_{ik}) - E(R_i))(E(R_{ik}) - E(R_j)) \tag{7}$$

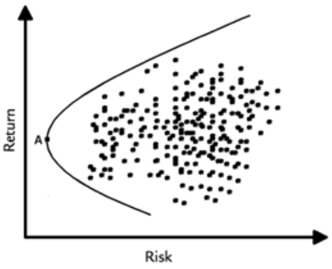

Figure 1. Region of feasible portfolios (after Figge 2004).

An asset can be understood as any entity money can be invested in. While financial asset managers can invest money e.g. in share companies NRM assets can be manifold and need to be defined in the problem context. If, e.g., the investment decision problem is to find an optimal portfolio of different tree species to optimize forestry returns every tree species considered could be defined an asset. If a set of *n* assets is defined, a set of feasible portfolios differing in the share of individual assets is established and the portfolio risk and return are computed. Three assets X, Y and Z having a share $w_X = 0.5$, w_Y 0.2 = and $w_Z = 0.3$ form one possible portfolio with a specific portfolio risk and portfolio return. Changing the shares of the individual assets leads to a different portfolio with a different risk and return. In Figure 1 every point represents one possible portfolio. Given a specific risk level a portfolio manager can easily determine the return that is associated to a specific portfolio of assets. The line in Figure 1 represents the most advantageous risk-return combinations (Figge 2004) where point A represents the portfolio with the lowest risk. However some portfolio managers may be aiming to achieve a higher return and may therefore be willing to accept a higher level of risk. In this case they have to move their portfolio along the upper portion of the line until the desired return or level of risk they are willing to accept is reached.

3. CASE STUDY – ELLEN BROOK CATCHMENT, PERTH

The Ellen Brook catchment is located north east of Perth and covers an area of 715km^2. Due to its high nutrient load input to the Swan River, this catchment is considered a priority catchment in which waterway health needs to be improved. In 2006 the Western Australian Government announced funding of AUS$1.437 million to be invested by the Swan River Trust's Drainage Nutrient Intervention Program (DNIP) to reduce nutrient loads entering the Swan River from the Ellen Brook. Out of 50 proposed sites, 29 sites that were on Government owned land were evaluated. All data used in this study, including criteria scores, criteria weights as well as cost data were provided by Swan River Trust officers and consultants. The computations were performed with the multi-criteria analysis tool (MCAT, Marinoni et al. 2009) which is a user-friendly software package providing multi-criteria analysis functionality as well as combinatorial optimisation algorithms.

3.1. Computation of benefits and subsequent optimisation

To evaluate the different decision options with multi criteria analysis, a set of performance indicators must be defined. Figure 2 shows the criteria categories and criteria being used to define the utility of an option. The criteria weights, which measure their relative importance, were set in consultation with stakeholders. The evaluation matrix being used in this case study cannot be shown due to its large size. The assigned criteria scores were qualitative and ranged from 1 to 10 where the higher the score the better the performance. These qualitative scores were provided by an environmental and engineering consultant who comprehensively assessed the catchment on behalf of the Swan River Trust (GHD 2007a, 2007b). The cost data being assigned to the intervention sites were similarly provided by this consultant. The costs are discounted costs over a period of 25 years which is the assumed lifecycle of the intervention sites. The locations to be evaluated were categorized according to their stream order: main stem, major and minor tributary sites.

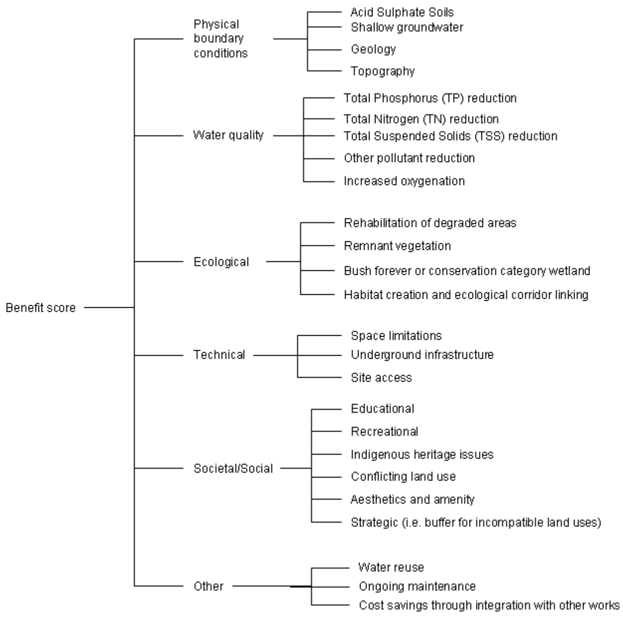

Figure 2: Criteria hierarchy.

4. RESULTS OF THE COST UTILITY ANALYSIS

The results of the CUA and the subsequent optimisation for a budget of A$1.437 million indicate that only major and minor tributary sites but no major stem sites should be funded (Table 1). The major stem sites return high MCA utility scores and represent sound options however due to their high cost these options return a lower benefit cost ratio which is the reason why they are not part of the Knapsack solution.

Table 1. Results of the CUA and the subsequent optimization subject to a budget constraint of AUS$ 1.437m.

A Hydrological categories	**B** Intervention site	**C** Benefit after MCA[*] [-]	**D** Cost [k$]	**E** BCR	**F** Fund?
Main stem sites	Site 7	0.41	636	0.00064	No
	Site 1a small NF[**]	0.227	136	0.00167	No
	Site 1b small NF, small SW[**]	0.44	485	0.00091	No
	Site 1c large NF, large SW[**]	0.548	958	0.00057	No
	Site 23	0.424	636	0.00067	No
	Site 24	0.35	636	0.00055	No
	Site 11	0.368	636	0.00058	No
Major tributary Sites	Site 20	0.317	48	0.00659	**Yes**
	Site 43	0.4	58	0.00689	**Yes**
	Site 41	0.519	48	0.01081	**Yes**
	Site 8	0.577	92	0.00627	**Yes**
Minor tributary Sites	Site 20a	0.366	29	0.01262	**Yes**
	Site 31	0.245	91	0.00269	No
	Site 26	0.285	91	0.00313	**Yes**
	Site 27	0.285	91	0.00313	No
	Site 28	0.285	91	0.00313	No
	Site 29	0.285	91	0.00313	**Yes**
	Site 30	0.285	91	0.00313	**Yes**
	Site 34	0.261	91	0.00286	No
	Site 32	0.285	91	0.00313	**Yes**
	Site 33	0.285	91	0.00313	**Yes**
	Site 35	0.285	91	0.00313	**Yes**
	Site 36	0.285	91	0.00313	**Yes**
	Site 37	0.391	91	0.00429	**Yes**
	Site 38	0.391	91	0.00429	**Yes**
	Site 42	0.211	91	0.00232	No
	Site 44	0.285	91	0.00313	**Yes**
	Site 45	0.285	91	0.00313	**Yes**
	Site 46	0.285	91	0.00313	**Yes**

[*]MCA used: Compromise Programming, [**]NF: Nutrient filter, SW: Sedimentation wetland

5. CONSIDERATIONS OF CLIMATE CHANGE

The results presented in Table 1 are not accounting for changes in the regional climate implying changes of temperature and precipitation. For the south western regions of Australia the projected rainfall change for the year 2030 relative to 1990 is between -5 and -7 % (CSIRO 2007a, CSIRO 2007b). The probability for this projection is greater than 70%. These figures are based on a climate scenario A1B which is based on a world population that peaks in the middle of the century and declines thereafter assuming a balance between fossil intensive and non-fossil energy sources (IPCC 2007). Given these projected dryer conditions, it is likely that smaller tributaries in catchments may run dry for greater periods of time or at least seasonally. Neglecting climate change for medium to long-term investments may result in building intervention measures at locations which could potentially run dry. These sites cannot perform their original purpose, i.e. to remove nutrients from the water, which would make these investments ineffective. However this does not automatically call for the exclusive funding of sites at the major stem which may have a higher likelihood of not running dry. The proposed intervention sites at the major stem are very costly and – as the cost-utility analysis showed – not as cost efficient as the minor or major tributary sites.

5.1. Application of Modern Portfolio Theory for the Ellen Brook

For the following portfolio analysis we considered three assets: main stem, major and minor tributaries where we aim to find the risk-return characteristics of different shares of these three assets. The return of an asset will not be given in monetary terms but will be quantified by aggregating utility scores obtained by multi-criteria analysis. We may plausibly assume that dryer climate conditions will have an effect on water quality criteria, water reuse and ecological criteria. The scores of these criteria were therefore subject to change and systematically reduced indicating an inferior performance. We will consider a climate change scenario for the year 2030 with a projected reduction in precipitation and the following probabilities (CSIRO 2007a).

Table 2: Probabilities of precipitation reduction scenarios for the region around Perth (from CSIRO 2007a).

	Reduction in precipitation	
Scenario	< -10%	> -10%
2030	0.75	0.25

We stress that this is an illustrative application for a real world case study based on a variety of assumptions. The aforementioned systematic reduction in the qualitative criteria performance scores was not a result of a sophisticated modeling procedure. Besides the projected reduction in precipitation, increases in temperature which may lead to an increase in evapotranspiration are not taken into account. Moreover, no spatial variation within the catchment has been considered. And finally, the probabilities for the climate change scenarios were not modelled specifically for the study area but were taken from small scale models that are based on just one climate scenario (A1B). Besides all the uncertainties and assumptions, we aim to illustrate the use of a combined application of combinatorial portfolio optimisation and portfolio theory which may be applied in a variety of other natural resource management problems where more accurate data and models are available. Based on the data in the adjusted scores in the evaluation matrices (2 matrices were needed, one with scores for the precipitation scenario <-10% and one for the scenario >-10%), utility scores and benefit cost ratios were computed. To avoid biases in the subsequent portfolio analysis utility scores and benefit-cost ratios were averaged within each asset. Summing up the scores of the individual sites within the three assets was not possible as the score would then have depended on the number of sites with the minor tributary sites by far outnumbering major tributary and major stem sites.

5.2. Results of the analysis based on modern portfolio theory

The results of the portfolio analysis are shown in Figure 3. Each of the 2000 points in this chart represents a portfolio consisting of different proportions of the three assets: major stem, major and minor tributaries. The proportions were randomly determined and the risk return computations where performed for each of the 2000 individual portfolio compositions using the equations given in section 2.3. Figure 3 shows that the lowest risk (and the lowest return) is returned at point A. This point represents a portfolio that exclusively consists of the asset major stem. Points B and C stand for a portfolios consisting 100% of minor tributary (B) and major tributary (C), respectively. Since we aim to attain as much return for a given level of risk, we have to move at the edge of the point cloud between points A and C indicating that the portfolio of assets should exclusively consist of the assets major stem and major tributary, but should not include the asset minor tributary. This is in contrast to the findings shown in Table 1 where a portfolio exclusively consisting of major and minor tributary sites - which is the edge of the point cloud between points B and C - was suggested.

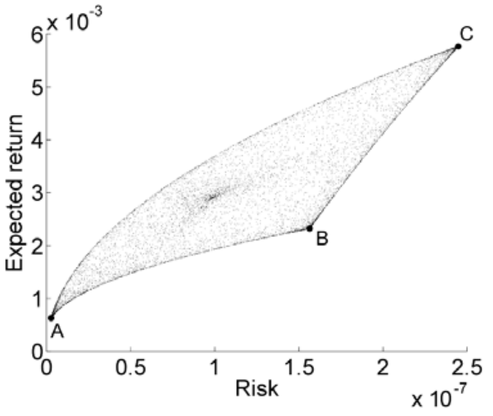

Figure 3: Possible portfolios of the assets main stem (A), minor tributary (B) and major tributary (C).

6. DISCUSSION AND CONCLUSIONS

The findings based on modern portfolio theory are counterintuitive to the result of the previous CUA which indicated that no major stem sites should be funded. The results of the CUA have a strong focus on cost efficiency and the selection of sites heavily depends on the benefit cost ratio. This implies that even exceptionally beneficial options are unlikely to be part of the selected portfolio if their costs are high. The presented results of the CUA do not imply any future uncertainties. Performing simulations with the CUA along criteria performance scores gives insight into probabilities of benefits achieved but there is no link to a risk component which is accounted for if modern portfolio theory is applied. We suggest that if asset returns are quantified with a triple bottom line score as provided by multi-criteria analysis, CUA and subsequent combinatorial optimization should not be conducted in isolation but should be jointly used with MPT if future uncertainties are to be taken into account. We believe that the application of portfolio theory has considerable potential to be used more frequently in natural resources management.

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