Principal component analysis for decision support in integrated water management

H. Helness, S. Damman, E. Sivertsen and R. Ugarelli

ABSTRACT

A general methodology for holistic sustainability assessment of measures in integrated water management based on principal component analysis (PCA) was developed. Application on data from three cases demonstrated that PCA could be used to rank alternatives, assess differences between groups of alternatives and the main properties responsible for this, and account for the impacts of measures on different dimensions of sustainability. The results demonstrated the general applicability of the method. For all cases a combination of measures/options yielded the most sustainable solution. The absence of a single clearly most optimal solution highlights the need for a transparent and systematic analysis, which can be obtained with the presented methodology.

Key words | integrated water management, PCA, sustainability

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INTRODUCTION

Aquatic ecosystems worldwide are subjected to pressures from agricultural intensification, pollution from industry and transport, and urban development. Climate change will exacerbate these by changing rainfall patterns and temperature regimes (IPCC 2014). In addition, these multiple pressures, threatening achievement of the United Nations Sustainable Development Goals (SDGs) (UN 2016), will be influenced by political and cultural changes. Increasing knowledge of the complex interaction between these multiple pressures has created a call for integrated approaches in water management (UN Water 2016). In this context, a methodology for holistic evaluation of the sustainability of alternative mitigation and adaptation measures is needed.

Sustainability assessments (SA) should cover the environmental, economic and social dimensions. To include results from different disciplines and manage potential conflicting issues within and between different SDGs or different policy areas, an integrated assessment of measures is required. Different outputs, including priorities of different stakeholders, can be structured in a transparent and objective manner in sustainability assessment frameworks (SAF) that can be used to compare alternatives using selected criteria. In general, a case with n alternatives and m criteria results in a matrix of n rows and m columns with $n \times m$ values that describe the alternatives according to the chosen criteria.

The common dilemma for a decision maker in such situations is to handle the amount and complexity of data and avoid losing important information on the way to the final decision. Alternatives can be compared by multi-criteria decision analysis (MCDA). Velasquez & Hester (2013) provided a comprehensive review of common MCDA methods and discussed their applicability to different situations by evaluating their relative advantages and disadvantages. However, complex comparison tables with detailed ratings could hinder full understanding of the alternatives. Also, commonly used MCDA methods fail to address correlations between criteria, which may result in a sub-optimal decision.

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Principal component analysis (PCA) is a potential solution for dealing with high correlation where many correlated variables may be reduced to two or three principal components, allowing for visualisation of the merits and demerits of alternatives in scatter diagrams or bar charts.

In this study one common method for MCDA based on PCA has been applied on data sets from three different studies. The purpose was to develop a general methodology for holistic SA in integrated water management, suitable in a range of cases from assessments at the strategic level to detailed assessment of technological solutions.

METHODS

Principal component analysis

PCA is a widely used multivariate data analysis method. It is particularly useful for data with collinearity and more variables than samples. In the context discussed here, the criteria in the SAF are the variables and the alternatives to be compared are the samples.

Based on the original variables, PCA calculates a set of new variables that describes as much as possible of the variance in the data. The new 'variables' are named principal components (PCs). The PCs will be ranked according to how much of the original variance they explain: PC1 will explain the most variance, PC2 the second most and so on. Calculation of PCs may be done with several methods. Here, the singular value decomposition method was used and performed with commercially available software, Unscrambler X 10.4 (Camo Analytics). The number of PCs to include in a given case can be based on a criterion for the explained variance. This is calculated for each PCA. A criterion of >98% was the default used in the calculation software. Often only one or a few PCs are needed to sufficiently explain the variance in the data, simplifying significantly the evaluation.

The results of a PCA are given as scores and loadings for each PC. The scores give the values of each alternative and the loadings give the values of each variable on the corresponding PC.

To ensure equal contribution from each observation and variable it is normal to standardise the data by subtracting the mean of all observations for each variable, i.e. mean-centring, and dividing by the standard deviation of the same variable (Martens & Næs 1991).

In the SA presented here, the observations are not mean-centred but scaled so that the optimum value of each variable is 0. The data in a SAF may also be normalised to a common scale, e.g. 0–10. For the PCA, each variable is in addition standardised by dividing by its standard deviation.

Different weight can be given to each variable by dividing each variable with different user-defined factors, e.g. to include the priorities of decision makers. However, this will not be discussed here.

The contribution of each variable to the score for a given PC and observation can be found by multiplying the loadings for that PC with the variable values for that observation. This gives the contribution of each variable to the score value. The relative contribution of each variable, i.e. the percentage, may also be calculated.

When several PCs are needed, the Euclidian distance may be used, i.e. the square root of the sum of squared scores from all contributing PCs:

$$d_i = \sqrt{PC_{i,1}^2 + PC_{i,2}^2 + \ldots + PC_{i,j}^2}$$

where d is the Euclidian distance for alternative i, and j is the number of contributing PCs. The relative contribution of each variable to the Euclidian distance can be found using the individual relative contributions for each variable.

SAF for the cases

The data sets used in this study all originate from SAFs that were developed to assess the sustainability of the current situation and alternative water management options for Oslo in Norway, Accra in Ghana and Riversdale in South Africa. These were of the same structure as in the EU-FP7 project TRUST (Alegre *et al.* 2012). The frameworks identified objectives, which were measured by several (m) criteria. Several (n) alternatives were identified to address the challenges. They were of different type, some technical, others focused on governance. For all cases the result was a matrix of n rows and m columns with $n \times m$ values that described the alternatives according to the chosen criteria (Appendix 1).

Data set 1/Oslo

Alternatives for future water supply were analysed to adapt to expected impacts from: (A) population growth, (B) increased industrial water consumption, (C) aging infrastructure and (D) climate change. Four different measures were evaluated: (a) reduction of water demand at a uniform rate of 1% per year; (b) reduction in leakage from the network at a rate of 1% per annum for the first 3 years; (c) installation of micro-turbines to utilise the kinetic energy from water flowing downhill to the water treatment plants; and (d) combining different raw water sources. In addition, three combinations of these measures were included giving in total seven strategies (a, b, c, d, a + b, a + b + c, a + b + d).

The seven strategies were assessed with respect to 11 criteria that described the impacts, included priorities of the decision makers and compared the foreseen situation in 2040 relative to the current situation (2013). The evaluation was based on technical–economic criteria and in addition greenhouse gas emissions. Social criteria were not included so the range of criteria was more limited than required for a full SA. The evaluation has been reported by Venkatesh *et al.* (2014).

Data set 2/Accra

Thirty-six alternative designs for roof rainwater harvesting (RWH) to meet demands of different size households were analysed. The designs were grouped in three groups: 'Basic', including only collection and storage; 'Intermediate', including also a water distribution system; or 'Advanced', including in addition a water disinfection system. Technical performance, environmental, economic and social sustainability criteria were included in the SAF. Technical performance was based on historic rainfall and roof size and storage capacity. Environmental criteria were based on LCA results for each design. Costs and savings were compared with buying tanker water. Long-term economic performance and payback time were selected as economic criteria. Acceptance, ease of operation, social capital, scope for entrepreneurship, resource independence, and health facilitation were the social criteria considered, with a set of more specific indicators defined for each criterion.

The sustainability of the 36 alternative designs was described by 19 criteria. The assessment was done in dialogue with local stakeholders, and has been reported by Damman *et al.* (2013, 2017).

Data set 3/Riversdale

Seven different adaptation strategies to meet expected climate change impacts on societal development due to expected future water scarcity were assessed: (A) business as usual regarding water resources and water cycle services (WCS); (B) add additional water source; (C) change water allocation system; (D) change land use in catchment; (E) change WCS towards water re-use; (F) reduce water loss from main pipe from reservoir; (G) improve demand management.

The SAF for the seven alternatives included 29 criteria based on the local municipalities' existing plans and compared indicator values for 35 years into the future with indicator values for the current situation. The assessment was at strategic level and involved local stakeholders. The SAF has been reported by Helness *et al.* (2017).

RESULTS AND DISCUSSION

Ranking of alternatives

In Oslo, seven different strategies and 11 criteria resulted in a matrix with 88 individual values when the status quo, i.e. no change in the system or practice, was included. The underlying assessment was based on thorough analysis of the different criteria. However, due to its complexity the resulting matrix was clearly not well suited for ranking the strategies.

To obtain an objective, although relative, ranking in such cases, PCA can be used. In the PCA the different alternative strategies are given scores which represent the distance from the common intersection of the PCs (origin) where the score is 0. The criteria chosen to assess the sustainability all have 0 as the most sustainable value. A value of 0 for the combined score for all the criteria in the PCA would represent the ultimate, most sustainable situation, although it may be hypothetical, e.g. zero cost, zero negative environmental impact and zero negative social impact are desired even if impossible in practice. Comparing the scores of the different alternatives gives a relative ranking of the sustainability of the strategies as measured by the chosen criteria. The results with equal weight on all criteria are shown in Figure 1, which is based on the first PC, which accounted for 99.6% of the variation in the data.

Compared with an 8×11 matrix with 88 individual values, Figure 1 gives an improved overview of the alternatives and provides a better basis for making a good decision. The different criteria are integrated in the sustainability score for each strategy. The high (>99%) explained variation indicates that the main differences between the strategies were well accounted for. The fact that this was obtained with only one PC indicates criteria with very high co-variation.

The PCA-based ranking indicated that the combination of measures (a + b + c) to reduce water loss and improve energy efficiency in the existing water supply would be more sustainable. This was also reflected in the relative importance of the criteria where energy per m^3 supplied was the criterion with highest importance followed closely by water supplied per capita, leakage percentage, chemical use per m^3 supplied and energy use per capita. All of these will favour solutions with reduced water loss and reduced energy for water transfer from additional sources.

Grouping of alternatives and identification of main properties

The methodology can also be used with complex data sets where more PCs are required, as in Accra, where detailed technical designs for RWH were compared. The results from the PCA of RWH designs with a scatter plot for the scores on the first two PCs are shown in Figure 2. The score plot showed clear differences in sustainability score between the three main groups of designs: Basic, Intermediate and Advanced, and differences within the three groups. These were related to e.g. choice of material in the storage tank, where ferro-cement (FC) was evaluated to be more sustainable than the commonly used plastic tanks (PP). One PC was required to account for 85% of the variation between the designs. An additional 8% was accounted for by the second PC.

With PCA, it is of interest to evaluate the number of PCs required and this can be done by assessing the incremental increase in explained variance for each added PC. If the analysis indicated that one PC is sufficient, the PC1 scores can be used. If two PCs are required, the distance from the origin to a given data point can be calculated as illustrated in the left-hand part of Figure 2. With more significant PCs, this can be generalised by using the Euclidean distance in an n-dimensional space.

In the case from Accra, four PCs explained 99% of the variance. A combined score with four PCs could be computed to rank the designs as described in the previous section. However, the overlapping results with several designs having similar scores indicated that household preferences would be important. The differences in sustainability between the main design groups and the main reasons for this were therefore more relevant questions. This could be assessed with only two PCs, reducing the complexity and improving the understanding of the data.

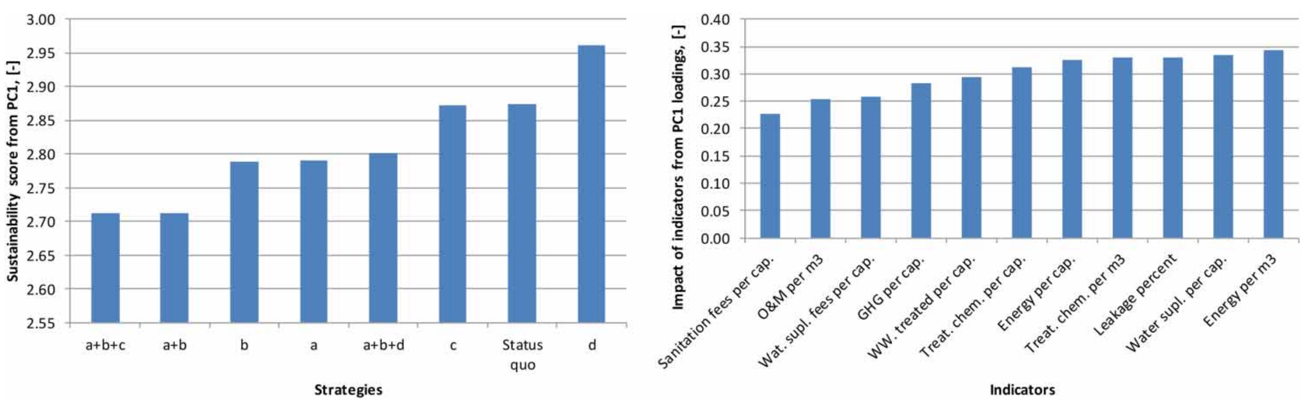

Figure 1 | Comparison of alternatives for water supply in Oslo: ranking of strategies using PCA scores (left) and influence of criteria on assessment using the PCA loadings for the criteria (right).

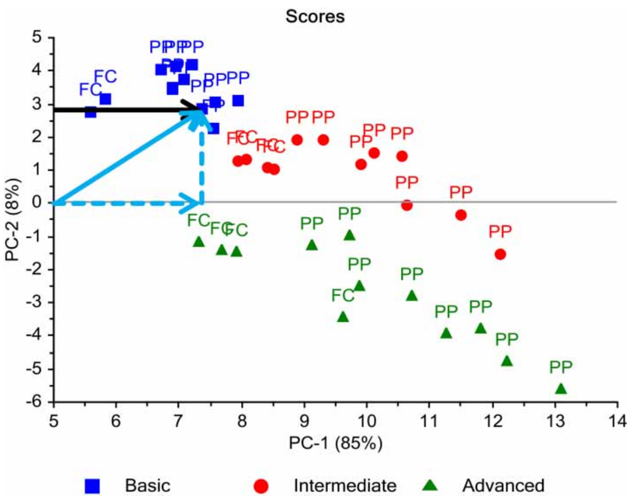

Figure 2 | Comparison of alternatives in RWH design alternatives in Accra: system type and storage tank material (FC, ferro-cement; PP, polypropylene).

Use of PCs has the advantages compared with common MCDA that all criteria and alternatives can be carried through the evaluation, avoiding potential bias of the results due to the discarding of criteria or alternatives in the course of the MCDA. As with other MCDA methods, the criteria can be weighted according to the perspective of a decision maker.

Accounting for contribution from different dimensions of sustainability

While the combined score (or loadings) give readable information in bar charts, some of the complexity of interactions which can provide fruitful and transparent grounds for discussion in a dialogue with well-informed stakeholders may be lost. A format that is easy to understand without losing details would clearly be desired. This would be valuable e.g. in an exercise with stakeholders to see the effects of different weighting done by decision makers and be needed to discuss the effect on different dimensions of sustainability. To this end, spider diagrams may be suited and have also been used by others (e.g. van Leeuwen 2013) for comparison of criteria for different alternatives.

Figure 3 shows results for the 29 criteria in the SAF used in Riversdale on a normalised scale of 0–10 where 0 is worst. In Figure 3, the expected impact on the chosen sustainability criteria if no measures are implemented and water availability is decreased by 10% less rain is compared with the current (2015) situation. The sustainability criteria are grouped so the impacts on the different dimensions defined in the SAF as well as the impact for individual criteria can

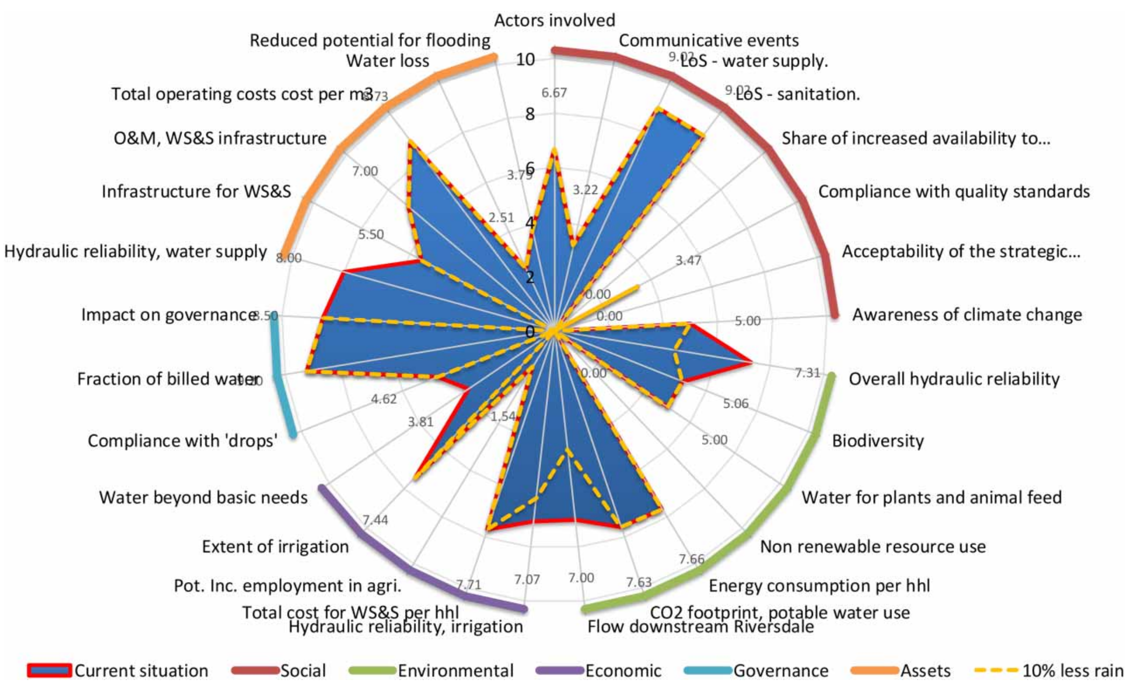

Figure 3 | Spider diagram with results for Riversdale, normalised to a scale of 0–10: current situation and expected future situation if no adaptation measures are implemented and the available water resources decrease due to 10% less rain.

be assessed. However, Figure 3 only shows one alternative in comparison with the current situation, and there is a limit to the number of additional alternatives that can be included before the spider diagram becomes unreadable. In general, one will therefore need to compare many spider diagrams to perform a full analysis even with a limited number of alternatives.

How the different dimensions of sustainability are influenced by alternative measures can also be found from the PCA by assessing the contribution from the criteria in each dimension.

Figure 4 shows the ranking of the different strategic options including the contribution to the sustainability scores from the five dimensions used in this assessment with one PC (left) and three PCs (right). The first PC explained 95% of the variance. The second and third PC explained an additional 3% and 2% respectively.

Considering that the optimal score is defined as 0, the PCA indicated that alternative F would be most sustainable, but also that the differences between alternatives could be small.

With one PC, the main variation was described (95%). This shows that the contributions to the sustainability score were largest from the economic, asset and environmental related criteria. With two (data not shown) and three PCs, additional variation (3% and 2%, respectively) was described. The contributions from the social and governance criteria increased, and the contribution to the scores from the social criteria became as important. A detailed evaluation revealed that this was mainly related to two criteria: *share of increased water availability to community* and *acceptability of the strategic alternative*, for PC2 and PC3 respectively. Considering that the PCA reflects variance and correlations, the differences between the alternatives were largest as measured by the economic, asset and environmental criteria, and there was considerable correlation between these. However, accounting for differences as measured by social and governance criteria would be required in a more detailed assessment.

To understand the scores on a given PC in terms of the original criteria, the contribution to the score from a criterion can be found using the loadings for the criterion on the corresponding PC. This may give additional insight into the contribution of individual criteria. However, the results demonstrated that a combination of measures/options would yield the most sustainable solution for Riversdale.

The findings from Riversdale are in line with the results from Oslo, where a combination of measures was also indicated. In the Accra study, the results showed that the best solution depended on the local situation and preferences of the household.

CONCLUSIONS

Water resources are under pressures. This calls for integrated water management strategies that take into account information from different disciplines. The decision makers' dilemma is how to combine all aspects and find the most optimal solution or alternative when the problem at hand is complex and a variety of solutions exists. A general methodology for holistic SA of measures in integrated water management based on PCA was developed. Application on data from three cases demonstrated that PCA

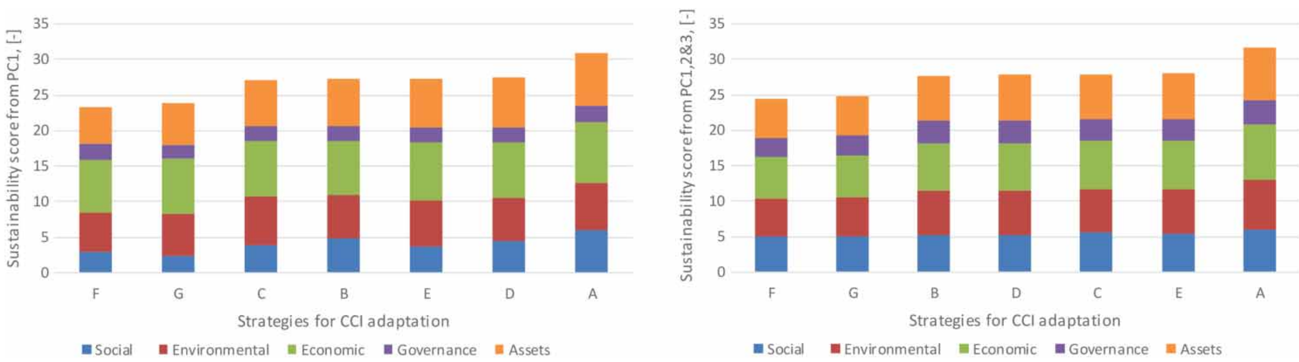

Figure 4 | Comparison of alternatives in Riversdale including the relative contribution to the sustainability score calculated with PC1 (left) and with PC1, PC2 and PC3 (right).

could be used to rank alternatives; assess differences between groups of alternatives and the main properties responsible for this; and account for the impacts of measures on different dimensions of sustainability. The results demonstrated the general applicability of the method. In all cases, the best solution depended on the local situation and preferences of decision makers. The common absence of a single clearly most optimal solution highlights the need for a transparent and systematic analysis, as obtained with the presented methodology.

SUPPLEMENTARY DATA

The Supplementary Data for this paper are available online at http://dx.doi.org/10.2166/ws.2019.106.

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