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Environmentally-Sensitive Water Resources Planning

I. Methodology

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Abstract. In this paper, the traditional problem of matching supplies to competing demands, referred to as *water resources planning* (WRP), is re-visited. With the pressure of continuing growth in the world's population, efficient development and management of available water resources are of greater importance than ever before. It is equally important in today's world that the environmental implications of any activity should be minimised. The aim of this research is to develop a methodology for including environmental considerations in the WRP process. This is achieved by weighting the costs of the various water resource options (both constructional and operating) to reflect their environmental impacts, prior to their inclusion in an economic planning model. The effect of such a weighting procedure is to encourage the selection of environmentally-friendly schemes at the expense of environmentally-damaging ones. The objective function of the combined methodology is to minimise the total environmentally-adjusted costs, discounted to a base year. A comprehensive planning tool named ENRES has been developed to carry out this task. The model allows the environmental impact assessment of all development options, either source components or transfer structures, to be undertaken prior to running the allocation procedure which is carried out by means of an optimisation technique. With the help of all the facilities provided, the model can be used in a planning exercise both with and without environmental considerations. In this way, it is possible to quantify the cost of environmental impacts in the planning process.

Key words: composite programming, EIA, quantification of environmental impacts, RESPLAN, water resources planning

1. Introduction

In recent years, water management has become more complicated not only because of the more sophisticated way we use water but also as a result of changing attitudes towards sustainability, which has become a pioneering concept since its popular definition given by the World Commission on Environment and Development (1987). Water used to be regarded as a natural resource to benefit which did not need protection. Now it has been recognised that water itself needs protection from mankind since it is an essential component of the living world, providing habitats for fauna and flora, as well as supporting a burgeoning human population. This brings environmental issues to the heart of the matter. In fact, the consideration of environmental issues is not new since it dates back to the 1960s. However, as in all scientific disciplines, the issue has become more complicated with the added pressure from newly-introduced national and/or international legislation together with the raised awareness of interest groups and the public. Therefore, tackling this issue is no longer possible with the traditional analytical techniques; new computational tools are needed which are capable of expressing the problem explicitly and solving it effectively. It is an added requirement in today's scientific world that the tools devised should have additional features such as user-friendliness and/or ease-of-use. To that end, this paper introduces a new methodology to include environmental concerns in the WRP context thereby aiming to improve the quality of that decision-making by identifying what appears to be the best-solution for satisfying the objectives considered.

1.1. WATER RESOURCES PLANNING (WRP)

Management of water resources systems comprise a series of activities ranging from deciding which storage scheme to develop to how it should be operated. WRP, however, can be defined as matching future demands to potential resources, satisfying some pre-set objectives such as cost-effectiveness or environmental quality. The end product of WRP is a development plan for some future period, normally 20 to 30 years (Simonovic, 1989; Jamieson, 1985). As such, WRP mainly encompasses three types of activities: (1) assessment of available water resources (supply forecasting), (2) assessment of future water requirements (demand forecasting) and (3) matching procedure between available resources and forecasted demands (development strategy).

At the *development strategy* stage which involves matching future demands to potential resources, three fundamental questions need to be addressed (O'Neill, 1972; Jamieson, 1985) namely:

- Which resources should be developed?
- In what order should these resources be developed?
- To which areas of need should the resources be assigned?

Given a set of possible schemes of various sizes and locations, each with an associated cost and yield, a strategy which seeks to answer the above questions can be termed *water resources capacity expansion planning and project scheduling* in which the 'best' solution is sought. The process involves searching a very large number of possible permutations and combinations of sources, links and demand centres (O'Neill, 1972; Haimes, 1977). In recent years, there has been a shift towards a participatory approach to allocating water resources to an increasing number of interest groups competing for the same water resources. This is particularly proposed by national and international water authorities such as European Environmental Agency and US Environmental Protection Agency (EPA, 2003).

Whatever approach is used in addressing the above questions, the objectives have to be identified prior to the matching procedure. Several objectives can be devised depending on the characteristics of the exercise undertaken. Thereafter, the objectives need to be expressed in a practical form so that a search procedure can be applied. Perhaps the most obvious objective is to minimise the overall economic cost. However, since the US Water Resources Council formally established the objectives of water and related land-resources planning activities in 1973 (Water Resources Council, 1973), environmental-quality has become an important issue in planning procedures. Identification of the objectives is dictated by a number of factors including the nature of the water industry and the capability of the analytical procedures. The objectives used in this research are restricted to economic-efficiency and environmental quality. As a result, the main concern is how the above questions should be addressed if the environmental issues are considered during the planning stage.

1.2. CONSIDERATION OF ENVIRONMENTAL ISSUES IN WRP

Consideration of possible environmental impacts at the outset is essential for sustainable water resource development. Moreover, early consideration of such issues should improve future decision-making and may save considerable time and effort in later planning stages (Lutz and Munasinghe, 1994).

Consideration of the environmental-quality objective in the form of either maximisation of environmental enhancements or minimisation of detrimental effects on the environment is often cumbersome since the overall environmental quality depends on many parameters, most of which are not easy to quantify. In practice, there are two main approaches for quantifying environmental objectives relating to project analysis or planning. The first approach is to use cost-benefit analysis by including environmental costs and benefits expressed in monetary terms, which is carried out using economic-valuation techniques. In environmental benefit-cost analysis, two further environmental costs are taken into account in addition to normal capital and operational costs, namely, environmental-protection costs to reduce some of the project's adverse effects and the environmental costs of other adverse effects not stopped by the conservative measures (Hufschmidt *et al.*, 1983). The former reflects the additional investments which follows the normal investment costing procedure. The latter requires the use of environmental-valuation techniques. Similarly, the environmental benefits from any environmental enhancements due to a project are treated as additions to the normal project benefits. The environmental benefits may result from the project itself as in the case of reservoirs, or they may be gained from the additional investments associated with the main project. For example, a water-supply scheme utilizing a polluted river may require improvements to the river, which would constitute an environmental enhancement of the river environment and should be considered in calculating the overall project benefits. To this end, the environmental economic analysis of projects with the Net Present

Value (NPV) criterion can be expressed by the following equation (Dixon, 1986):

$$\mathrm{NPV} = B_{\mathrm{d}} + B_{\mathrm{e}} - C_{\mathrm{d}} - C_{\mathrm{p}} - C_{\mathrm{e}} \tag{1}$$

where B_{d} are the direct project benefits; B_{e}, the external (and/or environmental) benefits; C_{d}, the direct project costs; C_{p}, the environmental protection costs and C_{e}, the external (and/or environmental) costs. It should be noticed that the cost and benefit terms included in the above equation are discounted terms, using a carefully-selected discount rate and time horizon (Lutz and Munasinghe, 1993; Munda *et al.*, 1995; Lutz and Munasinghe, 1994).

The second approach is to use multi-criteria decision-making techniques to take into account environmental objectives in planning. Obviously, these require prior formulation of environmental-quality objectives using quality parameters or a composite index to cover all environmental issues. Three main practices of multiple-objective WRP can be gleaned from the literature (Howe, 1976; Schramm, 1973) viz: (1) to formulate the overall planning problem using an objective function which minimizes the costs incurred and a set of other objectives which constrain the economic objective; (2) to make alternative plans, each of which reflects the most satisfaction with one objective, and to leave the selection of the best plan to the decision-making organization on the basis of value judgment or by carrying out a further trade-off analysis using a multi-criteria decision-making technique, and (3) to obtain one objective function by attaching weights to the various objectives, with a view to making them commensurable. A detailed discussion including the review of the available techniques in relation to both approaches can be found in Yurdusev (2002). Examples of these approaches in WRP can be found in O'Neill (1972), Water Resources Board (1973), Miller and Byers (1973), Haimes (1977), Kitson (1982), Stephenson (1982), Harhammer (1982), Bleed *et al.* (1985), Chaturvedi (1985), Kitabatake and Miyazaki (1989), Razarvan *et al.* (1990), Major and Schwarz (1992), NRA (1994), Raju *et al.* (2000), Simonovic *et al.* (1997), Quazi (2001) and Mimi and Sawalhi (2003).

This paper proposes a combined approach in which environmental impacts of individual projects are quantified by means of a multi-criteria approach. Thereafter, the outcome of this analysis is used in an economic model to provide an environmentally-adjusted economic plan. The concept was first formulated in late nineties (Yurdusev and Jamieson, 1977) and a complete coverage for the mature form is provided below.

2. The Approach to Integrating Environmental Objectives into WRP

2.1. CONCEPTUAL BASIS

As mentioned previously, large-scale WRP, particularly at the national scale, is characterized by a large number of options which potentially meet the water requirements at all demand centres. Moreover, allocating water from sources to demand centres is extremely complex even when restricting the decision-making to a single objective. Faced with the enormous number of options and the complexity of the problem, it is too difficult to formulate the problem as multi-criteria in the first place. The multi-criteria formulation would require the consideration of all environmental quality parameters either separately or together, not to mention the problem of quantifying them. This approach would only be possible for the evaluation of a single project where the numbers of parameters are manageable. The multiobjective evaluation of large-scale planning problems has been restricted to techniques employing a single objective function and several constraints, some of them dedicated to the satisfying other objectives. Therefore, the proposed methodology for including environmental concerns in the planning process has to be based on using a composite environmental index reflecting all environmental concerns in the objective function which is then formulated as the minimization of total discounted costs of overall plan. This effectively means that economic efficiency and environmental quality objectives are considered simultaneously within the objective function rather than within the constraints. This could be regarded as an attempt to merge the two main ways of tackling non-economic objectives referred to in preceding sections (extension of benefit-cost analysis and multi-criteria analysis). The costs in the objective function include what might be called *environmental net costs*. This somewhat unusual term is chosen since normally cost minimization process does not consider standard project benefits. Here, the intention is to include the normal project costs (capital and operational) plus environmental costs and environmental benefits in the objective function, the latter two terms being combined to form the net environmental costs. The methodology proposed may seem similar to the environmental cost benefit analysis previously mentioned since environmental objectives are expressed in monetary terms. However, it differs from that approach because:

- the monetary units would not be real but rather fictitious costs expressed in monetary units, which would only show the degree of environmental performance;
- the methodology proposed uses a composite environmental-quality index, allowing the inclusion of as many environmental parameters as desired, which basically means that a pre-trade-off analysis between the environmental objectives is required;
- the composite index itself, would be obtained by means of a multi-criteria decision-making technique.

Bearing in mind that the value of environmental objectives is not real, basically this approach can be said to have an objective function which takes the form of the weighted sum of economic and environmental objectives. These weights are assumed equal unless a further weighting analysis such as the one put forward by Simonovic and Bender (1996) is considered.

2.2. INTEGRATION OF ENVIRONMENTAL IMPACTS INTO THE OBJECTIVE FUNCTION

In order to include environmental considerations in an objective function based on minimizing the total discounted cost of development, the environmental concerns must have the same unit, which basically means a monetary valuation. Therefore, it is necessary to determine the environmental impacts to quantify/measure them prior to valuing them in monetary terms. However, since water resources projects have various impacts, even the quantification of them is sometimes very difficult; never mind the valuation in monetary values.

In developing a methodology for including environmental considerations in large-scale WRP, the intention should be to avoid selecting environmentally-damaging schemes and tend towards selecting environmentally-friendly ones. This is achieved by using a composite environmental index, referred to as the "Environmental Impact Factor" (EIF) in the objective function in order to fulfil the previously expressed aim. The function of this factor is to increase the costs of individual schemes if they are environmentally damaging or to reduce them otherwise. Therefore, the 'best' solution would be pushed towards environmentally-good projects. Different EIF should be developed for the capital and operational costs since different environmental impacts are associated with each of these stages. If the impact takes place just after the construction of a scheme and does not continue, it is included in the factor associated with the capital costs. If it is continuous or caused by the operation of the scheme, it is included in the EIF relating to the operational costs. This can be expressed in mathematical terms as follows: Given a planning study including n costed projects, with capital and operating costs of project i expressed as CC_i and OC_i respectively, and the associated Environmental Impact Factors as CEIF_i and OEIF_i, then the objective function of the optimization technique would be:

$$\text{Min.} \sum_{i=1}^{n} \{\mathrm{CC}_i + \mathrm{CC}_i \times (\mathrm{CEIF}_i - 1)\} + \{\mathrm{OC}_i + \mathrm{OC}_i \times (\mathrm{OEIF}_i - 1)\} \tag{2}$$

The second term in each parenthesis represents the environmental costs or benefits. If the scheme is environmentally damaging, the resulting environmental cost would be added to the standard project costs. Otherwise, any environmental benefit gained would be incorporated in the function as a negative cost. This will enable the environmental cost/benefits to be expressed in monetary terms.

It should be noted that these environmental costs and benefits are not real but nevertheless, are capable of reflecting how environmentally damaging or friendly the scheme is in comparison with others considered in the planning process. It has been assumed that environmental costs and benefits are proportional to the size of the project, which is a limitation of the proposed approach. In some cases, this assumption may not be justified. However, the assumption was necessary in order to develop a mechanism for including environmental concerns within an existing WRP model. Therefore, no pretence is made that multiplication of the actual construction and operation costs by an EIF factor provides a realistic estimate of the environmental costs and benefits: it is simply a mechanism which is intended to force the selection procedure towards the more environmentally-friendly options. From the above considerations, the following mathematical interpretations can be derived:

- EIF must be greater than 1.0 if a scheme is environmentally damaging
- EIF must be less than 1.0 otherwise

so that the costs of the schemes in the former are increased and those in the latter are decreased. The range of the EIF should be;

$$0 < \text{EIF} < b$$

The lower limit, 0, is obviously a theoretical value. When using EIF, it is necessary to assign a lower bound, say *a*, which is greater than 0 so that multiplying by EIF does not remove all cost from the objective function. In practice, it is virtually impossible to obtain a zero EIF anyway. The upper bound *b* should be reasonably greater than *1* so as to avoid the more environmentally-damaging schemes. To summarize, in terms of environmental performance of a project:

EIF = a if the scheme is nearly perfect (the ideal case),
EIF = 1 if the scheme is neutral and
EIF = b if the scheme is seriously damaging the environment (the worst case).

Having defined such a factor for environmental impacts, careful consideration should be given to it since all environmental concerns/impacts are included within it. To that end, the EIF is designed to be a composite index for all relevant environmental indicators. The inclusion of all environmental indicators in the one index requires the use of a weighting mechanism to obtain an overall value which reflects the environmental effects of a particular scheme. This is not only an operational necessity but also it provides an opportunity to assign more weight to the sensitive/critical/important facets. This obviously can be achieved by means of a Multi-Criteria Decision Making (MCDM) technique since such techniques are capable of tackling different criteria through a preference structure (e.g. weights, priorities or ordinal expressions). The selection of a particular method to be used depends on the nature of the problem (Lutz and Munasinghe, 1994). Since the aim in this study is to use a MCDM technique to obtain a composite index for environmental quality, it is important that (1) the method can be used as a basis for obtaining a composite numerical indicator through a weighting mechanism and (2) it should be simple. To this end, an extension of Compromise Programming (Zeleny, 1973), referred to as Composite Programming (Bardossy, 1983; Bardossy *et al.*, 1985) has been used in this study to develop environmental-impact factors. Composite Programming is based on obtaining a composite distance from a so-called an ideal point which represents full satisfaction of all objectives considered. In terms of environmental and economic objectives, the ideal point defines a situation where there is no detrimental effect on the environment when the system is fully developed (UNESCO, 1987).

2.3. DESCRIPTION OF COMPOSITE PROGRAMMING

The methodology uses the values of a series of aggregated indicators, each associated with a weight, to reach an overall evaluation value for the problem concerned. The basic indicators relating to the water- resources system under consideration are grouped and a higher level composite indicator (second-level indicator) for each group is obtained. Such an aggregation structure can be extended using as many steps as required until an overall final indicator is reached.

Prior to making an aggregation structure, the basic indicators must be selected so that the further compositions can be made. According to UNESCO (1987), when selecting environmental indicators, one has to consider the type of project, the degree of natural disturbance to be tolerated and the type of options to be left open for later use.

Having selected the basic indicators, the measurement units which either qualify or quantify the impact should be determined for each indicator. Physical, chemical or biological units can be assigned to the ecological indicators whereas productivity per unit of land area, average life span etc. are examples for quantifying the socio-economic indicators. Qualitative measurement units such as insignificant, low, moderate, significant and high can be used to indicate the effect on wildlife habitat or vegetation where quantitative measurement units may be inappropriate. However, the more the measurement units can be expressed quantitatively, the better.

The next step is to assign best and worst values to the basic indicators where the former represents the ideal conditions and the latter indicates the least favourable. As far as environmental quality is concerned, the best values characterise the minimum values while the maximum values represent the worst values for most basic indicators (UNESCO, 1987). For example, the best value for loss of farm land due to a particular project would be no loss whereas the worst value would be the greatest loss (Stansbury *et al.*, 1991). The best and the worst values define a range for each basic indicator, in which a particular project has an actual value, this being the estimate of the condition created by the project. If the condition could be observed, the actual value would be the value taken from the observed data. To carry out this task objectively, several observations, measurements and calculations may be necessary.

Composite Programming employs a double weighting mechanism. One is the *weights* for the indicators, which articulates the decision-maker's preferences with respect to the relative importance of each indicator. The other is what is called *balancing factors* given to the each group, in which a number of indicators is involved. Unlike weights, balancing factors are associated with the groups rather than each indicator. While the choice of weights emphasise the relative importance of the indicators in comparison with each other, selecting balancing factors refers to the significance of larger deviations in the indicators. The purpose of high balancing factors is to give more emphasis to the indicators which have large negative values (Goicoechea *et al.*, 1982).

Once the relevant indicators, associated boundary values (ideal and worst values), actual values and weights are determined, the first step is to normalise the basic indicator values (transposing them into the range of 0–1). This is undertaken to make all indicators comparable to each other, thereby avoiding their different units. Given the maximum value (Z_{i+}), the minimum value (Z_{i-}), the normalised value (S_i) of an actual indicator value (Z_i) can be calculated as follows,

$$S_i = \frac{Z_i - Z_{i-}}{Z_{i+} - Z_{i-}} \quad \text{or} \quad S_i = \frac{Z_{i+} - Z_i}{Z_{i+} - Z_{i-}} \tag{3}$$

where the choice is made to ensure that the S_i to be used in the following equations represents the relative position with respect to the best value. The next step is to calculate second-level composite distances for each second-level group of basic indicators by using:

$$L_j = \left[\sum_{i=1}^{n_j} \alpha_{ij} S_{ij}^{p_j} \right]^{1/p_j} \tag{4}$$

where i is the sequential number given to a basic indicator, j the sequential number of a certain group of basic indicators, S_{ij} the value of the basic index S_i within the second-level group j, L_j the distance from the ideal point of the composite of the n basic indices (S_{ij}) second-level group j, n_j the the number of basic indicators in a second-level group j, a_{ij} the the weights expressing the relative importance of the n basic indicators in group j, the sum of weights in any group being equal to one, p_j the balancing factor, which is equal or greater than 1, among indicators within the group j. The consecutive computations of higher-level composite indices are made in the same manner until a final composite distance for a system is reached.

This multi-criteria decision-making technique gives the opportunity to use different indicators from different categories in calculating an overall composite distance, which identifies the position of the system concerned with respect to the ideal state. Obviously the schemes with small composite distances are closer to the ideal state than those with large composite distances. UNESCO (1987) suggests that the alternatives with composite distances lower than 0.3 are sound projects. The composite distances between 0.3 and 0.6 shows acceptable schemes whereas those larger than 0.6 represent poor projects. By means of the composite distances of the options, it is possible to rank them.

2.4. DEVELOPMENT OF EIF FROM COMPOSITE PROGRAMMING

By matching the EIF concept to the concept of composite distance and the corresponding limits suggested by UNESCO (1987), it is possible to say that the neutral EIF value, 1, falls into the acceptable region, that is to say, somewhere between 0.3 and 0.6. This has been assumed to be 0.50, by applying a precautionary approach since when the value is 0.6, the scheme is still acceptable according to UNESCO (1987). Having matched the neutral value to an appropriate composite distance, the boundary values (the L values of 0 and 1) which indicate the ideal and worst situations, have to be matched to appropriate EIF values. Bearing in mind that the ideal situation is when $L = 0$, the corresponding EIF must be 0 since the EIF concept necessitates the removal of all cost associated with the scheme. With regard to the worst situation, the question arises as to what degree of cost increase is necessary to ensure that a scheme is unlikely to be selected. The answer has been taken to be that doubling the cost is a sufficient penalty. Furthermore, this is compatible with assigning 0 for EIF when $L = 0$ because same amount of cost would be removed/added for the same distances from the neutral point.

Having determined the main matching points, the question is how to connect these points. Since Composite Programming describes a region for the acceptable state, it would be preferable to use a gentle curve within the boundaries of the acceptable region. Moreover, if the curve were steeper towards the two extremes, the effect would be to push the solution towards the more environmentally-friendly schemes by deliberately exaggerating the EIF values. This suggests some form of exponential function, three of which have been considered, each having the following general form:

$$\begin{aligned} y &= ax^{b/c} && \text{if } 0 < x < 0.5 \\ y &= 2 - a(1-x)^{b/c} && \text{if } 0.5 < x < 1 \end{aligned} \tag{5}$$

where y is the EIF, x the composite distance (CD) of Composite Programming, a is a coefficient specified from the neutrality boundary value, with b and c being coefficients for a number of different EIF-CD functions. Three different functions are examined. The a, b and c coefficients for the trial functions are (1.41, 1, 2), (1.33, 5, 12) and (1.26, 1, 3).The functions are called formula #1, formula #2 and formula #3 respectively.

In selecting a suitable function for *EIF*, it is necessary to include a number of practical considerations for the ideal and worst points, where L values are 0 and 1: Firstly, it is difficult to define ideal and worst situations in practice as the corresponding theoretical *EIF* values previously mentioned in an optimisation procedure, will result in the complete removal of associated cost terms (EIF = 0). However, leaving ideal or worst points in place, but not allowing them to be used in practical calculations, it is possible to stay within the definable boundaries. To this end, the significance concept is introduced when defining the practical extreme situations, namely positive significant and negative significant, the former being the boundary of beneficial situations the latter being that of detrimental situations. The remaining assessment values are scattered evenly in between. These include negative moderate, negative small, neutral, positive small and positive moderate. These assessment values are attached qualitative values between 1 and 7; 1 for negative significant, 2 for negative moderate, 3 for negative small, 4 for neutral, 5 for positive small, 6 for positive significant and 7 for positive significant. The positions of the assessment values are specified with respect to ideal points. In an attempt to find the values of ideal and worst points that yield the most appropriate EIF values, five different sets of numerical values for the ideal and worst points given below have been evaluated together with the three different EIF-CD functions previously mentioned.

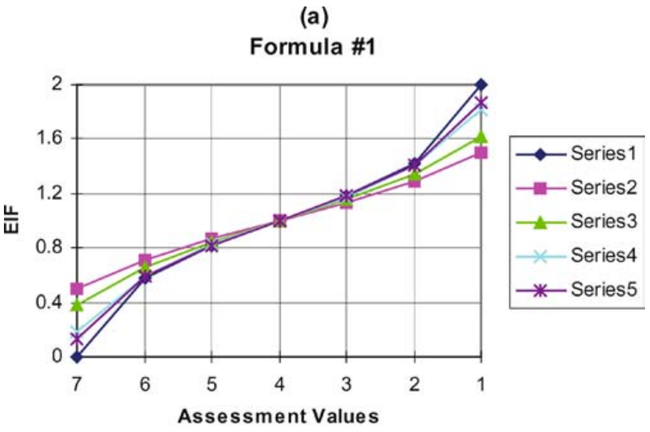
Data set	Best value	Worst value
1	7	1
2	8	0
3	7.5	0.5
4	7.1	0.9
5	7.05	0.95

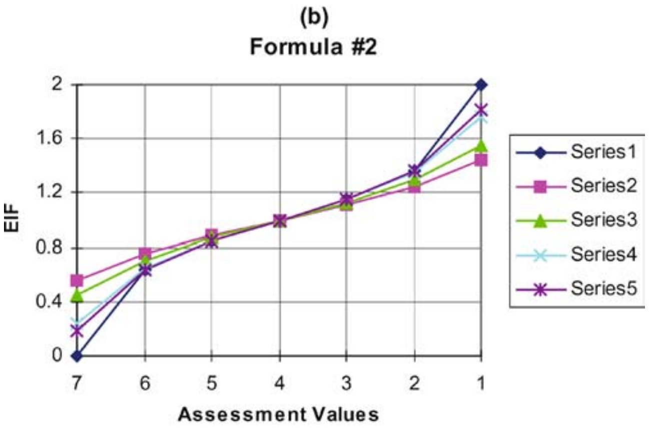
The standardised assessment values, calculated by means of Equation (3), and the corresponding EIF values of the previously specified functions are plotted in Figure 1. In selecting the appropriate function and data set, the main objective was to reach appropriate significant values. Therefore, it is concluded that EIF values of formula #1 calculated by means of data set 4 are the most appropriate. As a result, the function selected to transform composite distances into Environmental Impact Factors takes the following form:

$$\begin{aligned} y &= 1.41\sqrt{x} && \text{if } 0 < x < 0.5 \\ y &= 2 - 1.41\sqrt{1-x} && \text{if } 0.5 < x < 1 \end{aligned} \tag{6}$$

3. Integrated Environmental and Economic WRP Model

Having introduced the proposed methodology for integrating environmental considerations into WRP models in the previous section, it is now possible to build a model which embodies these concepts. The model is intended to facilitate the decision-making process in selecting a water resources development strategy which is economically-effective as well as environmentally-acceptable.





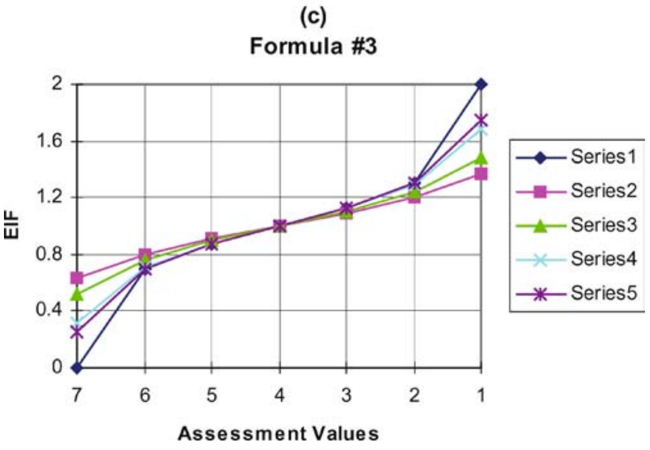


Figure 1. Environmental impact factors versus composite distances.

Bearing in mind the detailed description of the proposed environmental-assessment methodology, it will be apparent that the water resources model would be still basically an economic planning model. However, it could be classified as an environmentally-influenced economic planning model since the costs of the schemes considered are based not only on the engineering costs but also the environmental costs as reflected by the impacts of each scheme. The model developed has two main components: one being an economic-planning model which identifies the plan with the lowest total discounted cost, the other being an Environmental Impact Assessment (EIA) model which modifies the engineering costs, both capital and operating, depending on whether the scheme is environmentally-friendly or otherwise. To this end, an existing economic water resource planning model referred to as RESPLAN (Anglian Water Services, 1993) has been selected and a new EIA model has been developed which has subsequently been incorporated into RESPLAN. The name given to this combined model is ENRES which is derived from an *ENvironmentally-influenced RESplan model.*

3.1. THE RESPLAN MODEL

RESPLAN is an economic WRP model whose origins date back to the mid-seventies (Brew, 1976). The model uses a network of demand centres, sources and potential links connecting each source to the various demand centres. The development programme selected comprises a sequence of new sources and links needed to be constructed in order to meet projected demand at the minimal discounted cost (Anglian Water Services, 1993). The RESPLAN model employs an allocation technique based on heuristic programming, which dispenses with rigor and exactness but still retains the detailed representation of water resources systems (Page, 1984).

The RESPLAN model is primarily concerned with capital investment decisions with a view to determining: answers to the questions raised in section 1.1. Therefore, it does not include hydrological and water-quality aspects. The RESPLAN model consists of two modes: namely, allocation and costing models. Whereas the former is used to find the least-cost development programme, the latter is used to cost any programme, either the one produced by the allocation mode or any other plan. This feature is useful to provide a manual check on the least-cost solution of allocation or to answer "what if" scenarios, for example to determine the sensitivity of the plan costs to a particular source being excluded or the costs of a link element being increased. The structure of the model is shown in Figure 2.

The allocation process used in RESPLAN is an iterative procedure, in which a series of costed plans are produced for a pre-defined number of iterations, the allocation for each iteration being derived from the discounted unit costs obtained from the cost data of the previous allocation. Although the model is intended to determine the least-cost allocation, the algorithm does not guarantee global optimality. However, after, say, 100 iterations, the plan with the least discounted cost can be regarded as a good approximation of the optimal allocation (Page, 1984).

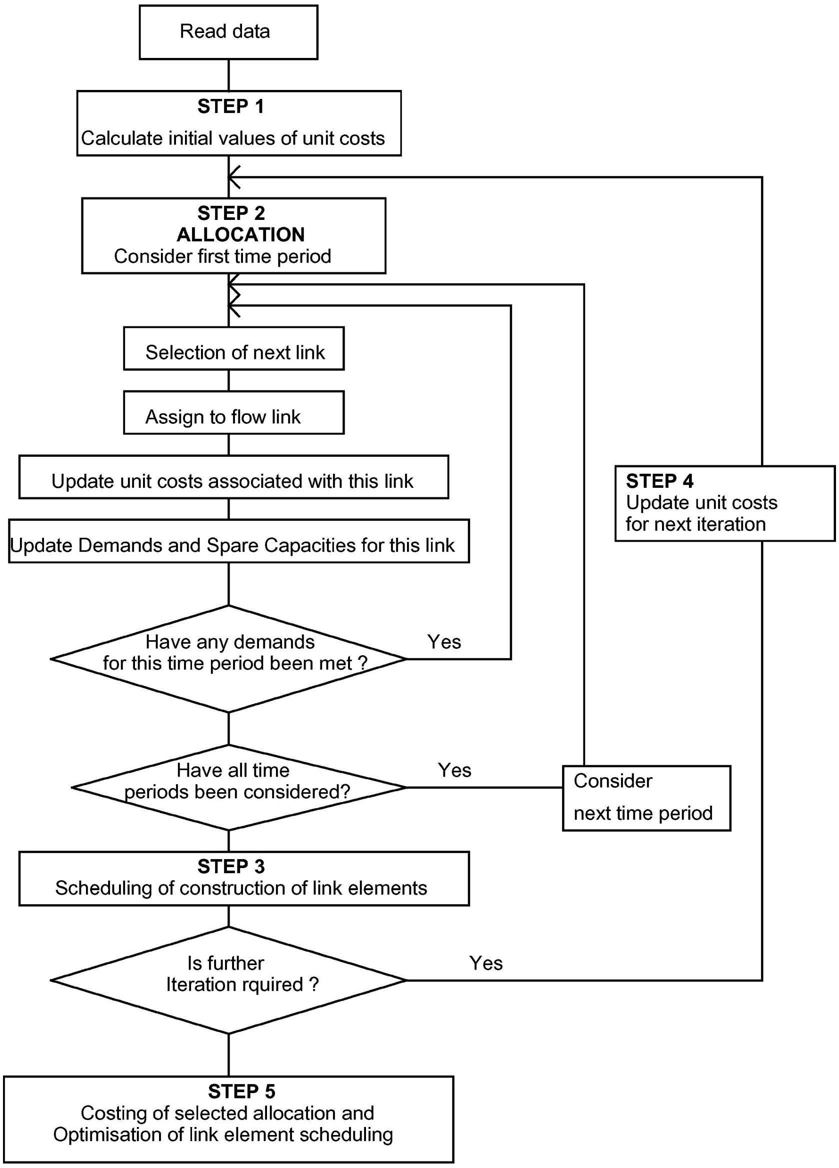


Figure 2. General structure of RESPLAN model, adapted from Anglian Water Services (1993).

The use of the RESPLAN model to form a constituent part of what is now the ENRES model stems from the availability of the model and the need for the application of ENRES to a particular region in order to show its applicability. Obviously, integrating an existing model with other computer codes necessitates access to the source code so that modifications, however minor, can be made. Moreover, the intention was to apply the methodology developed to the whole of England and Wales, for which the former National Rivers Authority (NRA) had published its strategy in 1994 (NRA, 1994). The NRA used the RESPLAN model throughout the planning study (Page, 1984). The case study is meant to repeat the NRA planning exercise but this time including environmental impacts so that it would be possible to see what might have been the NRA proposals had environmental considerations been explicitly taken into account. The results of the case study presented in Yurdusev and O'Connell (2004) would have been incompatible with those of the NRA had another model been used.

3.2. ENVIRONMENTAL IMPACT ASSESSMENT MODEL

The Environmental Impact Assessment (EIA) model employs the methodology previously described. As has already been implied, the EIA model is intended to produce Environmental Impact Factors (EIF) to screen a series of resource-development options in a WRP study (Yurdusev and Arı, 1997). The environmental information, impacts of projects and assigned relationships, together with the user's evaluations, form the inputs in calculating EIF, which comprise the main output from the model. Therefore, the model includes user-interaction as well as data retrieval and display facilities, as shown in the general structure of the model in Figure 3.

As can be seen from Figure 3, the operation of the model can be visualised as three main loops. The inner loop evaluates the environmental criteria for a particular scheme which are stored in generic data files either directly or by means of basic indicators, again stored in the generic data files. The middle loop performs the same analysis for the operational considerations if required to do so, whilst the outer loop enables other schemes involved in the study to be evaluated. In software engineering terms, a subroutine caters for the first loop, providing the values of subsequent-level indicators, prior to a further call on the same subroutine to form the second loop. The third loop is controlled by the number of schemes for which the EIA is to be undertaken. When it is required, the model presents a series options as seen in Figure 4 so that the user can either make a fresh run or use the assessment values of previous runs partially (option 2) or completely (option 3). The user can also alter the default weights associated with the impacts to carry out a sensitivity analysis. Using the user dialogue in Figure 5, the EIA of a scheme is undertaken based on four major impact categories namely; resource utilisation, quality implications, ecosystem implications and social implications. The model uses a series of impacts under these groups with respect to the project types as follows; reservoirs, groundwater schemes, direct river abstraction schemes, effluent re-use schemes, desalination projects, estuary developments, river/canal reaches and pipelines and tunnels. Demand management measures through which additional water can be provided can be included as a source within the model since there are two spare source types in the model. Demand management measures can also be considered in forecasting water demand (Froukh, 2001). Obviously, the appropriate cost figure

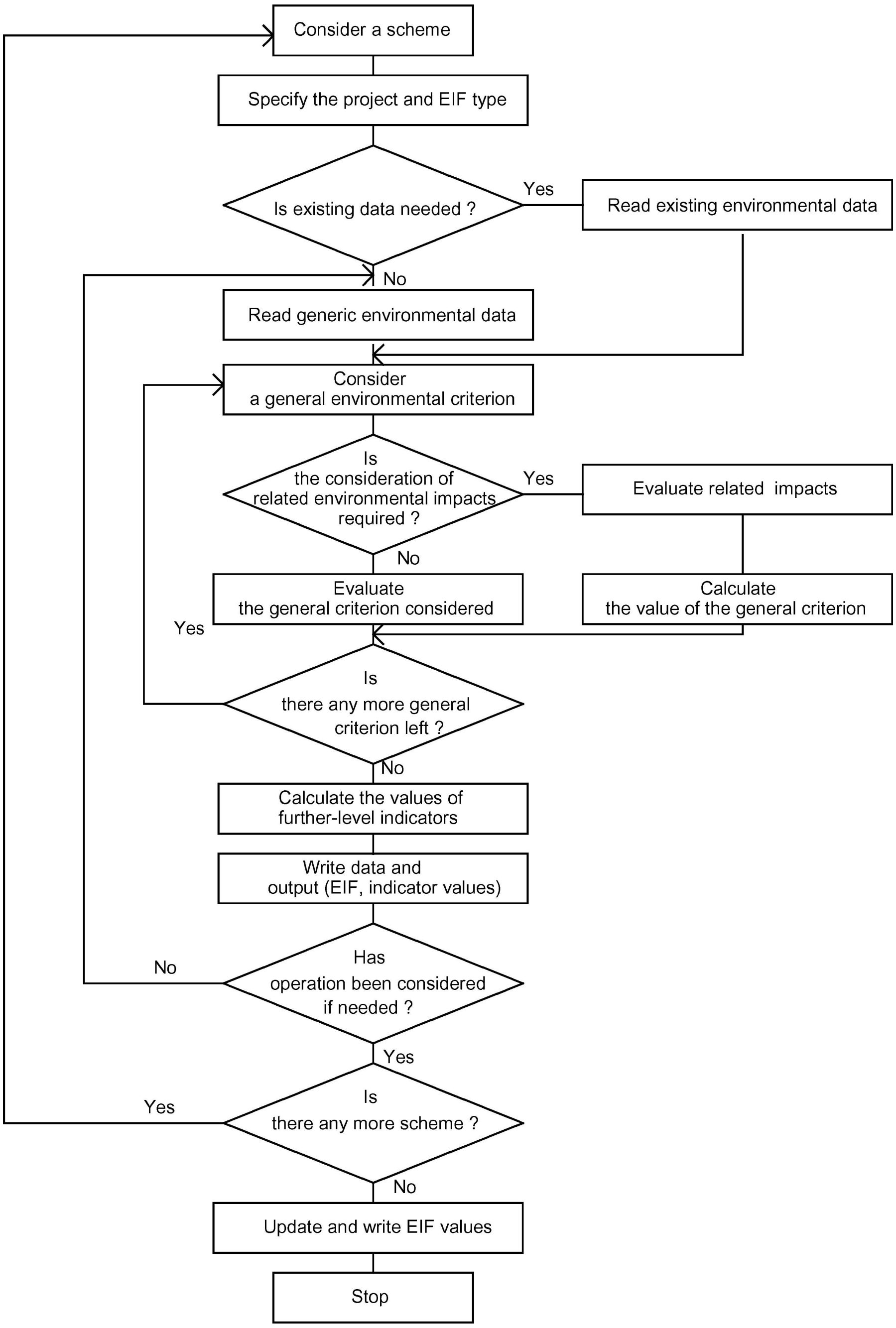
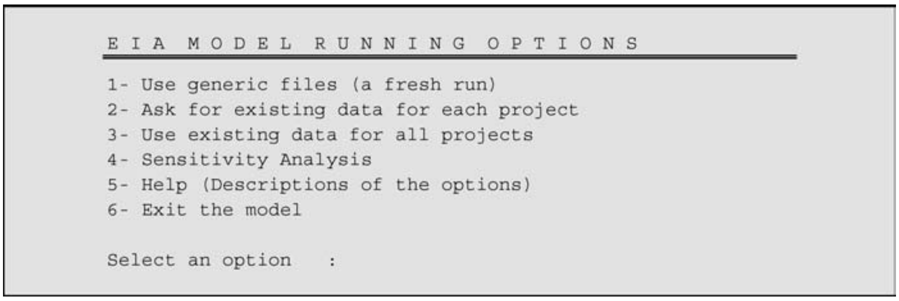


Figure 3. General structure of Environmental Impact Assessment model.

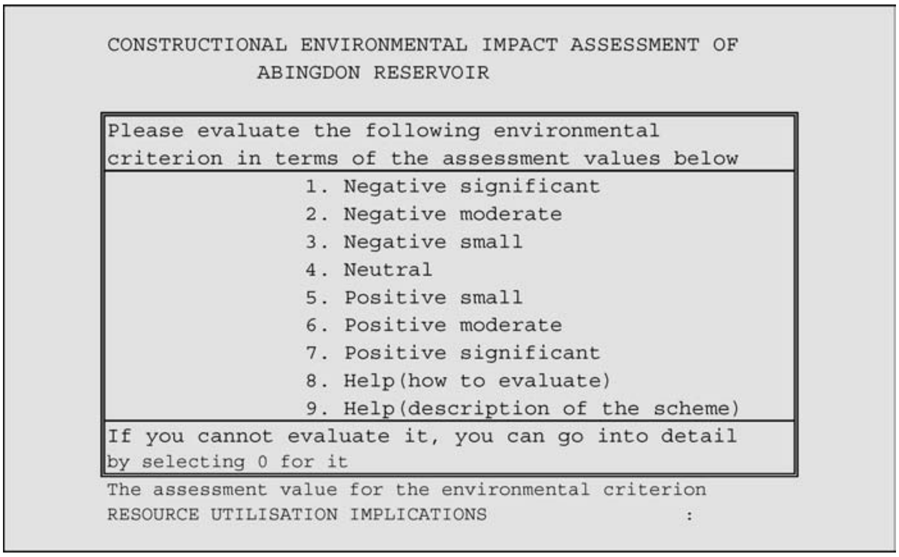


```
E I A  M O D E L  R U N N I N G  O P T I O N S

1- Use generic files (a fresh run)
2- Ask for existing data for each project
3- Use existing data for all projects
4- Sensitivity Analysis
5- Help (Descriptions of the options)
6- Exit the model

Select an option   :
```

Figure 4. EIA model running options.



```
CONSTRUCTIONAL ENVIRONMENTAL IMPACT ASSESSMENT OF
             ABINGDON RESERVOIR

Please evaluate the following environmental
criterion in terms of the assessment values below
                 1. Negative significant
                 2. Negative moderate
                 3. Negative small
                 4. Neutral
                 5. Positive small
                 6. Positive moderate
                 7. Positive significant
                 8. Help(how to evaluate)
                 9. Help(description of the scheme)
If you cannot evaluate it, you can go into detail
by selecting 0 for it
The assessment value for the environmental criterion
RESOURCE UTILISATION IMPLICATIONS                  :
```

Figure 5. Assessment of second-level indicators when generic data are used.

and the associated environmental impacts should be included in the model. If thee measure is a costless one, the cost figure associated would be zero. A large number of impacts based on the project types have been identified for this purpose whose definitions including some pseudo rules on how to assess them and aggregation structures can be found in Yurdusev (2002). The model is equipped with similar user dialogues to the one given in Figure 5 for different running options. The user is also provided with required knowledge including guidelines on how to assess a particular impact. As such the model works like a pseudo expert system by which the user can assess the impacts consistently (Yurdusev, 1999).

3.3. OVERALL MODEL

Combining the RESPLAN and EIA models produces an overall Environmentally-influenced Economic Planning System (ENRES) in which the EIFs are used to weight the real costs, both construction and operating, for various development options to reflect their positive or negative environmental impacts. To achieve this end, a Linker Program has been developed to couple these two models. The Linker Program was designed to enable RESPLAN to consider environmentally-modified cost figures. The program transforms the RESPLAN data by means of the EIF generated by the EIA model, creating a new data file. Whilst other data remains unaltered, those related to costs are modified. The format of the new file is exactly the same as the original data file so that RESPLAN reads it without any change to the input structure.

The whole purpose of the ENRES model is to carry out the planning exercise with and without environmental considerations so that a direct comparison can be made between them as illustrated in Figure 6. Therefore, the combined model includes all the individual components of RESPLAN and the EIA model so that they can be used individually and/or together. As can be seen from Figure 6, the model has two main capabilities, one being based on the joint use of the EIA and RESPLAN models the other being the RESPLAN model by itself. Whereas the former is used to carry out a planning exercise incorporating environmental factors, the RESPLAN model only produces an economic solution. The planning exercise considering environmental impacts is undertaken by first running the EIA model whose outputs are then transferred to the RESPLAN input file, prior to running the RESPLAN model. Both components are linked to the input files and produce separate output files. The output features include a joint display of the results for both solutions.

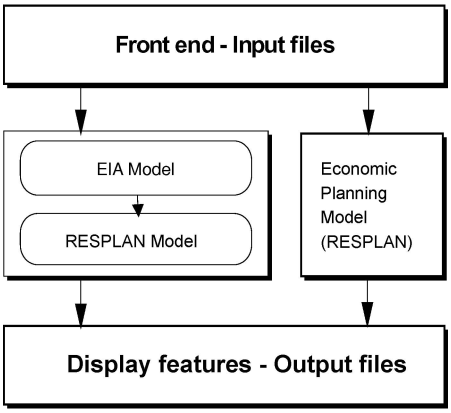


Figure 6. General structure of ENRES model.

4. Conclusions

The problem of integrating environmental considerations into large-scale WRP models has been investigated and a model for achieving this end has been proposed in this paper. The overriding objective was to establish a theoretical foundation on which a practical tool would be based. Moreover, the tool would need to be compatible with the nature of the problem which in this case was the initial screening of options with a view to meeting the planning objectives. Such tools are also useful where repetition of the exercise is needed at some time later when new data are made available or if the situation has changed. Since these tools are capable of storing the previous data as well as the results, new results can be evaluated in the light of the previous ones. Based on the findings of this research programme, the following concluding remarks can be made:

1. Without considering possible environmental implications from the outset, it is no longer possible to promote development of any kind as a result of environmental legislation that has come into force from either national or international authorities. The legislation is a reflection of the growing public awareness of the need to protect the environment.
2. Water is no exception. Since it interacts with land and air as well as social and ecological systems, planning for its future should take into consideration the physical, chemical and biological impacts. Moreover, bearing in mind that water resources assets have extensive economic lives, the long-term environmental effects need to be assessed. However, the broad scope of the WRP problem is a limiting factor since it restricts the level of environmental detail that can be realistically incorporated.
3. An extensive literature review has shown that theoretical, analytical and even computational tools to tackle environmental issues are available and well established. However, when it comes to dealing with a particular problem, implementation of such concepts can cause major difficulties, such as the quantification of impacts. Moreover, it was concluded that most Environmental Impact Assessment studies were conducted for individual projects rather than comparing a group of projects. Therefore, there is a need for problem-specific analytical tools which are capable of being used in practice. To that end, ruling out most of the analytical techniques mentioned in section 2, an attempt has been made in this study to develop a WRP methodology which specifically incorporates environmental concerns into the process to develop a practical tool.
4. In establishing the theoretical basis for this methodology, the concept was to consider the environmental impacts of individual components in a WRP exercise within an economic-planning model. This was achieved using an Environmental Impact Factor (EIF) by which the costs of a scheme are either increased or decreased depending on whether its impacts was detrimental or beneficial to the environment. Within the EIA study, the individual impacts are aggregated into a higher-level indicator until one composite index for a scheme is derived which

reflects the environmental performance of that scheme. This is achieved by using a multi-criteria decision-making technique referred to as Composite Programming. In the methodology developed which involves multiplying a construction and operating cost by an appropriate Environmental Impact Factor, there is an obvious difficulty when a link element, such as a river, has no associated costs. In this case, either the impact can be ignored or some surrogate costs introduced. If the latter approach is adopted, clearly there are a number of assumptions that could be made including using the operating cost of the source, the overall link or an equivalent element such as a pipeline or canal. Either way, it represents a potential shortcoming.

5. This has resulted in a WRP specific Environmental Impact Assessment (EIA) methodology being developed since existing EIA methodologies are generally applicable to specific projects where a detailed assessment is required. However, a screening study requires a systematic approach if large numbers of options are to be evaluated within a reasonable timescale. Therefore, as an integral part of the model developed, a systematic EIA procedure for WRP has been devised, with individual impact evaluations being quantified by means of a Multiobjective decision technique, Composite Programming. Some believe that such techniques are no longer of use in the water planning process. However, recent literature (Raju *et al.*, 2000; Mimi and Sawalhi, 2003, Srdjevic *et al.*, 2004) and scientific activities such as the latest IFAC Workshop (Modelling and Control for Participatory Planning and Managing Water Systems, 29 September–1 October 2004) suggest otherwise.
6. To assist with the Environmental Impact Assessment process mentioned above, an extensive list of environmental impacts has been developed, each with its own descriptive remarks to assist with the assessment.
7. In this study, an existing WRP model, RESPLAN, and newly-coded model for EIA have been coupled through a Linker program to provide an integrated planning tool. The resulting ENRES model is capable of undertaking a WRP exercise with and without considering environmental impacts so that a comparison is possible, the difference between the total discounted costs of the two plans being a measure of the price of environmental concerns. The ENRES model also includes data-editing, user-interaction, data retrieval, help and result-displaying facilities by which it is possible to:

   - prepare input data and edit where necessary;
   - undertake planning without considering environmental impacts;
   - carry out environmental impact assessments for the individual projects involved;
   - undertake the planning exercise incorporating the environmental evaluations;
   - repeat the planning exercise as many times as desired by modifying the existing data or by adopting a new data set and
   - display the outputs in text and graphical forms.

In addition, the model has the following facilities:

- a user-interface to direct the analysis and assess the environmental impacts;
- assistance when needed in the form of hypertext;
- input-output file organisation to allow different exercises to be undertaken.

8. The proposed methodology can be of help in formulating and exploring alternative development scenarios by incorporating different weights representing the preferences of different interest groups, since the different sets of weights will produce different development outcomes.. The interested parties can then use these scenarios to help resolve conflicts and to reach an agreement over the future use of water resources in a region.

In formulating ENRES, it was necessary to incorporate an existing WRP model since development of a new one was beyond the scope of this research programme. The need to access the source code limited the choice. As a result, RESPLAN was selected despite its known drawbacks. Therefore, any shortcomings in RESPLAN are automatically included in ENRES.

There is an obvious need for demonstrating such models on a case study. The model presented in this paper is applied to the whole of England and Wales and the findings of the case study presented in a companion paper (Yurdusev and O'Connell, 2005).

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