ORiON, Vol. 14, No. 1/2, pp. 17-35 ISSN 0259-191-X

DECISION SUPPORT SYSTEMS FOR ENVIRONMENTAL MANAGEMENT: A CASE STUDY ON ESTUARY MANAGEMENT

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ABSTRACT

In situations to do with the management of natural resources in the public domain there are often many 'interested and affected parties'. The opinions of how a given resource should be managed are as diverse as the parties themselves. Debates are frequently unproductive. We argue that in these situations the development of a decision support system (DSS) is a constructive way forward towards sound management practices. This approach enables existing knowledge to be integrated into a form that can be used immediately in decision-making. Furthermore, research can be optimally prioritised should greater accuracy or improvement in the initial DSS be required. We illustrate this approach by considering the problem of determining the freshwater requirements of estuaries. The pattern of freshwater flow into an estuary of a river that has been impounded is a management decision. This inflow pattern influences the state of an estuary. This in turn affects the fish that use the estuary. In this illustration we focus on these fish in developing a DSS. The DSS is then applied in a case study of the Krom River in the Eastern Cape.

1. INTRODUCTION

As the demand for natural capital such as water increases, so do the complexities of resource management; often characterised by dissension between social, economic, environmental and political issues. The dynamic nature of these interactions and their non-linear response to changes are difficult to predict, creating uncertainty and difficult to explain and difficult to defend. The result is often a debilitating, unproductive debate, which stifles progress and wastes resources. However, in recent times technological and organisational advances in managing information have provided new opportunities for supporting sound environmental decision making. The purpose of this paper is therefore to present a case study which illustrates the value of adopting a decision support approach to the management of natural resources such as estuaries. It is our belief that this is a necessary and appropriate response to the requirements of environmental management in the 1990's.

The value of adopting a decision support approach to resource management is not limited to the benefits arising from an improved basis for decision making. For example, as the approach focuses on making the best use of available information and also refines further information needs; cost-effective research is promoted. In our view, environmental decision support is taken to mean the process of :

- identifying information needs. *What information is required by resource managers to manage our resources wisely?*
- maximising the utility of existing information. *How can existing data and current understanding best be used to solve problems now?*
- managing the storage, retrieval and analysis of information. *How can data be stored and analysed in a way which supports managers by providing answers timeously?*
- developing techniques which facilitate environmental management based on both structured (collected and analysed information) and unstructured information (expert opinion). *Can we develop techniques which will (i) assist resource managers in making appropriate decisions and (ii) provide an efficient means of collating knowledge?*
- identifying the data and information collection requirements to enhance and validate decision support systems. *What data needs to be collected to improve our decision-making ability? Can we prioritise our data collection requirements? Can we develop cost effective monitoring strategies?*
- transfer of techniques and information to individuals and organisations

responsible for management and policy development. *How can we ensure that managers use the best available knowledge to make decisions? How can we ensure that managers use our decision support systems?*

- feedback and refinement of research responsible for original data and information collection. *How can we set research priorities which will enhance the DSS? How can we ensure that future research provides understanding to enhance management capability?*

2. DEVELOPING AN ENVIRONMENTAL DECISION SUPPORT SYSTEM

2.1 Statement of the problem

In recent years several authors have expressed concern about the possible effects of reduced freshwater inflow into South African estuaries (Begg 1978; Noble & Hemens 1978; Reddering 1988; Whitfield & Wooldridge 1994). The growing demand for assured water supplies has necessitated the construction of large storage dams, agricultural dams and barrages, and in some cases, inter-basin transfer schemes. Instead of being available as streamflow to estuaries, water is stored and subject to consumptive losses, including high evaporation. Not only is there a loss of streamflow (volume) due to impoundment, but there is also an alteration in the pattern of supply (seasonality and flow rate). As Reddering (1988) has noted, the equilibrium between successive periods of deposition by wave action and scouring by episodic events can be readily disturbed by modifications in river discharge. If the scouring potential of flood events is reduced by impoundment attenuation, it follows that an estuary may be open to the sea at a reduced frequency, thereby limiting the opportunity for key processes maintaining the estuarine habitat to occur. Begg (1978) has argued that closure of the estuary mouth along the north-eastern coastline of South Africa has become the artificial norm, and furthermore that this often occurs at the most critical time for inshore spawning and recruitment of estuarine dependent fish species.

2.2 Formulation of the approach

As demand for water increases, it is essential that the freshwater requirements of rivers and estuaries are well articulated and that suitable methodologies are available to assist in determining the optimal scheduling of freshwater allocations.

This decision support system is a first attempt to formulate a methodology, which addresses this need.

The decision support system developed in this example is a biologically meaningful management index, which is based on the integration of three key information sets. The first information set is the current understanding relating to the dependency of coastal fish species on the estuarine environment. The second is the preferred timing of the recruitment period for key species, and the third is the known environmental requirements for recruitment by juvenile marine fish.

2.2.1 Dependency score (DS_i)

Whitfield (1994a) has recently provided a revised estuary-dependence categorisation for fishes in South African estuaries, comprising five major categories (Table 1). Of the five major categories, only divisions Ia and IIa are totally dependent on estuaries. Categories Ib, IIb and IIc represent species which are at least partially dependent on estuarine systems, a large proportion of which could be regarded as marine/estuarine opportunists. Category III comprises mainly stenohaline marine species, which occur in low numbers in estuaries. Category IV consists of mainly euryhaline freshwater species, for which the degree of penetration into estuaries is determined primarily by salinity tolerance. Finally Category V includes obligate catadromous species which use estuaries as transit routes between marine and freshwater environments.

Table 1: The five major categories of fishes which utilize South African estuaries (*after* Whitfield 1994a)

<table>
<tr><td rowspan="3">I</td><td colspan="2">Estuarine species which breed in South African estuaries. Further subdivided into :</td></tr>
<tr><td>Ia</td><td>Resident species which have not been recorded spawning in the marine or freshwater environment</td></tr>
<tr><td>Ib</td><td>Resident species which also have marine or freshwater breeding populations</td></tr>
<tr><td rowspan="4">II</td><td colspan="2">Euryhaline marine species which usually breed at sea with the juveniles showing varying degrees of dependence on South African estuaries. Further subdivided into :</td></tr>
<tr><td>IIa</td><td>Juveniles dependent on estuaries as nursery areas</td></tr>
<tr><td>IIb</td><td>Juveniles occur mainly in estuaries, but are also found at sea</td></tr>
<tr><td>IIc</td><td>Juveniles occur in estuaries, but are usually more abundant at sea</td></tr>
<tr><td>III</td><td colspan="2">Marine species which occur in estuaries in small numbers but are not dependent on these systems</td></tr>
<tr><td>IV</td><td colspan="2">Euryhaline freshwater species, whose penetration into estuaries is determined primarily by salinity tolerance. Includes some species which may breed in both freshwater and estuarine systems.</td></tr>
<tr><td>V</td><td colspan="2">Obligate catadromous species which use estuaries as transit routes between the marine and freshwater environments</td></tr>
</table>

Based on the list of species provided by Whitfield (1994a), each species was allocated a Dependency Score (DS_i), reflecting the extent of dependency of the species on the estuarine environment (Table 2). Thus Category IIc species, being only partially dependent on estuaries scored lower than Category IIa species which are entirely dependent on estuaries. The score of an endemic species, regardless of the Category was increased by one point.

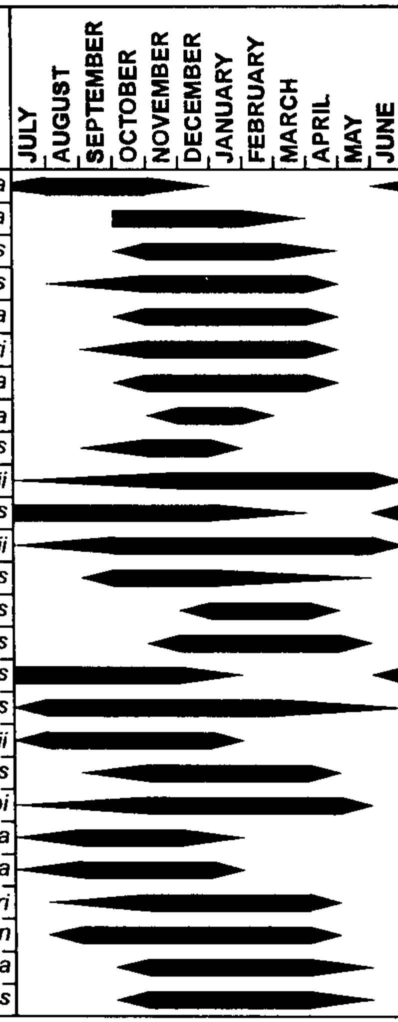
Table 2: Dependency Scores (DS_i) allocated to categories of fish

CATEGORY	DEPENDENCY SCORE (DS_i)
IIa	5
IIb	3
IIc	1
V	5
endemic	+1

2.2.2 Optimal recruitment score (ORS$_i$)

Whitfield and Kok (1992) have provided a summary of the recruitment periods for common coastal species in the Eastern and Western Cape Province, whereas Wallace & van der Elst (1975) give similar information on species from the KwaZulu-Natal region. Table 3 below summarises the species included in the model and their recruitment periods. Table 3 also indicates which of the 26 species occur in the vicinity of the two case study estuaries. The Optimal Recruitment Score (ORS$_i$) was defined as being 5 for the main immigration period, decreasing linearly to 0 towards the outer limits of the species recruitment period.

Table 3: Recruitment periods for common southern Cape species (after Whitfield & Kok 1992)



SPECIES	COMMON NAME	Krom
Acanthopagrus berda	River bream	
Anguilla mossambica	Longfin eel	●
Argyrosomus japonicus	Kob	●
Diplodus sargus	Blacktail	●
Elops machnata	Ladyfish	●
Johnius dussumieri	Small kob	
Leiognathus equula	Slimy	
Lichia amia	Leervis	●
Lithognathus lithognathus	White steenbras	●
Liza dumerilii	Groovy mullet	●
Liza macrolepis	Large-scale mullet	
Liza richardsonii	Southern mullet	●
Liza tricuspidens	Striped mullet	●
Megalops cyprinoides	Oxeye tarpon	
Monodactylus falciformis	Cape moony	●
Mugil cephalus	Flathead mullet	●
Myxus capensis	Freshwater mullet	●
Pomadasys commersonnii	Spotted grunter	●
Rhabdosargus globiceps	White stumpnose	
Rhabdosargus holubi	Cape stumpnose	●
Rhabdosargus sarba	Natal stumpnose	
Sarpa salpa	Strepie	●
Solea bleekeri	Blackhand sole	●
Stolephorus holodon	Thorny anchovy	
Terapon jarbua	Thornfish	
Valamugil cunnesius	Longarm mullet	

2.2.3 Mouth and axial salinity gradient multipliers (MSM_t, ASM_t)

Whitfield (1994b) has shown that the single most important factor associated with the abundance of larval and juvenile marine fishes in Eastern Cape estuaries is the axial salinity gradient. Figure 1 (see the end of this article) shows that the ichthyonekton densities of the Great Fish and Sundays estuaries, characterised by strong axial salinity gradients were more than 5 times greater than those recorded in the Kariega system, which had a poorly developed axial salinity gradient. Whitfield (1994b) has thus suggested that recruitment is only likely to occur to any significant degree if the axial salinity difference exceeds 20g.kg^{-1}. Recruitment was thus assumed to occur only at 10% of maximum when the axial salinity difference was less than 20g.kg^{-1}, increasing linearly to 100% as the axial salinity difference reaches 35g.kg^{-1}.

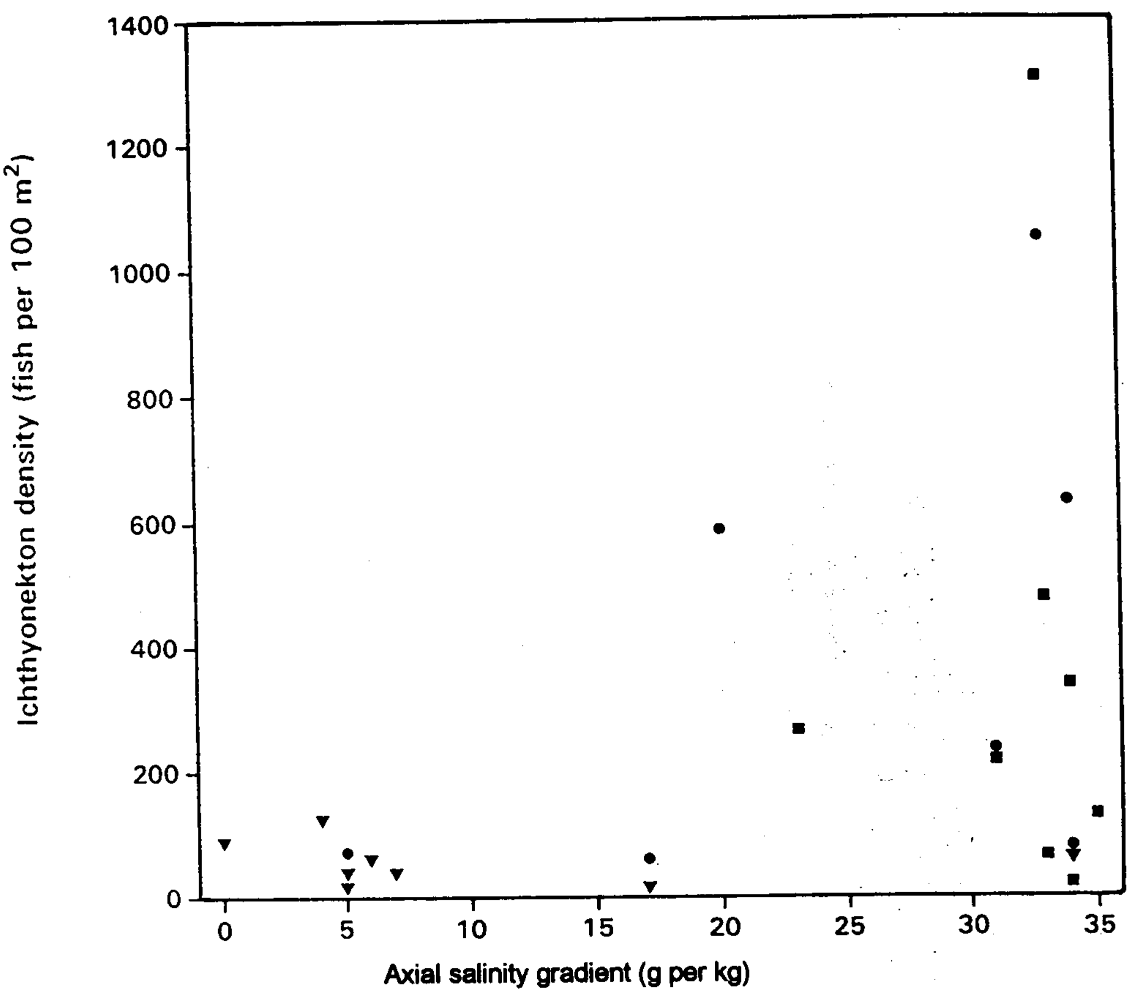


Figure 1: Ichthyonekton densities versus acial salinity gradient in each of three South African estuaries on the eastern Cape coast (■ Sundays; ● Great Fish; ▼ Kariega) (Whitfield 1994b)

A further, although more obvious, limiting condition is that the mouth must be open for recruitment to occur. Table 4 below shows the values assigned to the mouth condition and axial salinity difference multipliers, given the range in hydrodynamic conditions which may occur. The condition of the mouth and the axial salinity gradient are obtained by routing freshwater inflow scenarios through an estuarine physical dynamics model (Slinger, 1995).

Table 4: Multipliers for different hydrodynamic conditions

HYDRODYNAMIC CONDITION	AXIAL SALINITY MULTIPLIER (ASM_t)	MOUTH CONDITION MULTIPLIER (MCM_t)
Mouth open	-	1
Mouth closed	-	0
Axial salinity gradient > 20g.kg^{-1}	ASM_t = -1.1 + (0.06* axial salinity difference)	-
Axial salinity gradient < 20g.kg^{-1}	0.1	-

2.2.4 Fish recruitment index (FRI_t)

The above scores and multipliers were integrated into a single score, namely;

$$FRS_t = \Sigma_i\, MSM_t\, .ASM_t.ORS_{it}.DS_i$$

where :

FRS_t	=	Fish Recruitment Score at time t	
MSM_t	=	Mouth Status Multiplier at time t	($MSM_t = 0$ or $MSM_t = 1$)
ASM_t	=	Axial Salinity Multiplier at time t	($0.1 \leq ASM_t = 1$)
ORS_{it}	=	Optimal Recruitment Score of species i at time t	($1 \leq ORS_{it} \leq 5$)
DS_i	=	Dependency Score of species i	($1 \leq DS_{it} \leq 6$)

In order to normalise the score to account for the fact that fewer juvenile fish recruit in winter in comparison with summer, the Fish Recruitment Score is divided by the maximum Fish Recruitment Score which is possible for that particular day of the year. The result is expressed as a percentage. Thus;

$$FRI_t = \frac{FRS_T}{FRSMAX_t}.100$$

where:

FRI_t	=	Fish Recruitment Index at time t
FRS_t	=	Fish Recruitment Score at time t
$FRSMAX_t$	=	Maximum Fish Recruitment Index for estuary at time t

3. APPLICATION OF THE DECISION SUPPORT SYSTEM

3.1 The Krom estuary

Slinger (1996) has described the Krom estuary (Figure 2) as a narrow, sinuous water body extending for approximately 14 km from a permanently open mouth to a rock sill which forms the head of the tidal influence. As a consequence of the extent of impoundment in the catchment the only assured supply of freshwater is the 2×10^6 m^3 per annum allocated for ecological purposes, and is released from the Mpofu Dam. Thus on average the Krom estuary receives less than 2% of the runoff it would under natural conditions (Slinger, 1996).

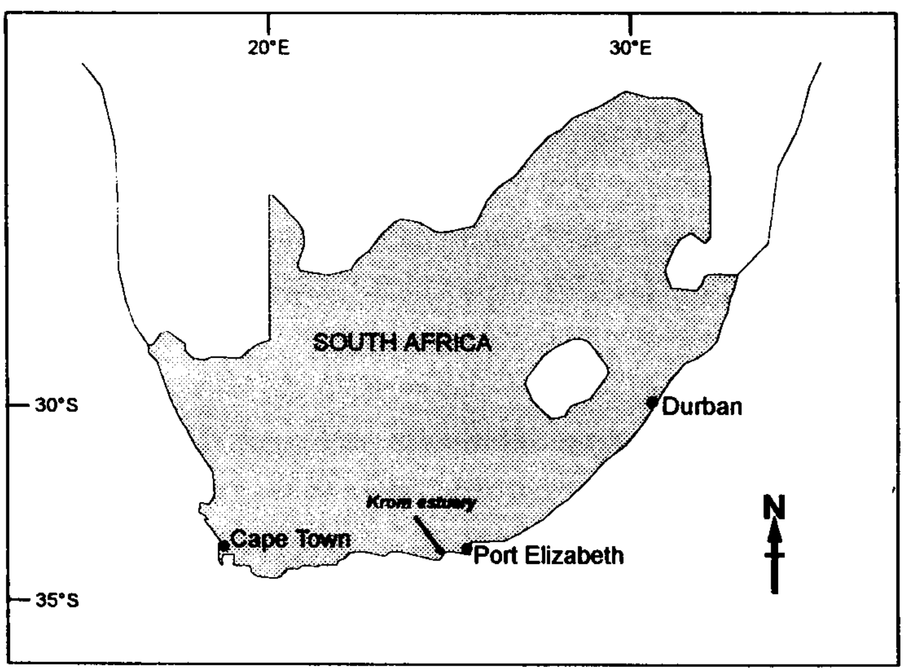


Figure 2: Location of the Krom estuary in South Africa

3.2 Freshwater release scenarios

Several runoff scenarios were selected for testing. The first is a typical runoff scenario under natural conditions, while the second is the current runoff pattern, where a monthly water allocation is released from the dam. The other three scenarios include an annual allocation for baseflow, a freshette and an annual flood. Graphs depicting these release policies are shown in Figure 3. Figure 3 is shown at the end of this article.

(i) Natural runoff scenario

According to Slinger (1996) the natural mean annual runoff (MAR) of the Krom estuary is approximately 120 x 10^6 m^3y^{-1}. Although the daily runoff values used in this exercise are simulation results, the natural seasonality and flooding of the Krom are nevertheless approximated. This scenario thus represents pristine conditions prior to the construction of the Mpofu Dam.

(ii) Present runoff scenario

The present runoff scenario consists of monthly releases over one day of one twelfth of the total annual allocation of 2 x 10^6 m^3y^{-1}. This release policy is aimed at preventing the occurrence of hypersalinity at the head of the estuary, and only the salinity in these regions is affected by these releases (Slinger, 1995).

(iii) Intermediate runoff scenario : 10% of the MAR

This scenario consists of a baseflow allocation corresponding to the evaporative requirement of 2.4 x 10^6 m^3y^{-1} and the 1 in 2 year flood volume (8.61 x 10^6 m^3y^{-1}) provided by Jezewski and Roberts (1986). The flood occurs in early summer, with a freshette of 1 x 10^6 m^3y^{-1} occurring in late summer, approximately 4 months after the flood.

(iv) Intermediate runoff scenario : 20% of the MAR

An early summer flood (October/November) equivalent to the 1 in 2 year flood (8.61 x 10^6 m^3y^{-1}), with a late summer flood of 2 x 10^6 m^3y^{-1} occurring four months after the first flood. The balance of the annual allocation of 24 x 10^6 m^3y^{-1} enters the estuary as continuous baseflow following the natural runoff pattern. As Slinger (1995) has noted, this allocation is double that of the scenario above.

(v) Intermediate runoff scenario : 40% of natural MAR

A similar flooding regime with an early summer flood (October/November) equivalent to the 1 in 2 year flood (8.61 x 10^6 m^3y^{-1}), with a late summer flood of 2 x 10^6 m^3y^{-1} occurring four months after the first flood. The remainder of the allocation (37.39 x 10^6 m^3y^{-1}) enters the estuary as continuous baseflow following the natural runoff pattern.

3.3 Results

Results of the simulations are shown in Figures 4 and 5. Figure 4 shows the daily fish recruitment score, while Figure 5 shows the daily fish recruitment index, normalised for the maximum possible score on the particular day. Figures 4 and 5 are shown at the end of the article.

(i) Natural runoff scenario

Under natural runoff conditions, an axial salinity difference greater than 20 $g.kg^{-1}$ is maintained for all but approximately two months of the year, coinciding with the low flow period in March. As a consequence, fish recruitment occurs at full potential, decreasing to 10% of potential for the low flow period in March. The mean score of the index for the year is 87.

(ii) Present runoff scenario

Under the present runoff scenario, the axial salinity difference does not even exceed $5g.kg^{-1}$, and as a consequence recruitment occurs only at a fraction of potential.

(iii) Intermediate runoff scenario : 10% of the MAR

The early summer flood creates an axial salinity difference of greater than 20 $g.kg^{-1}$ for approximately one month, permitting fish recruitment to occur to the maximum for the period mid November to mid December. The flood is well timed as it occurs at the time of year at which the maximum number of species are recruiting. The second flood does not induce an axial salinity difference of greater than 20 $g.kg^{-1}$, and consequently has no positive effect on fish recruitment. The mean score of the index for the year is 15.

(iv) Intermediate runoff scenario : 20% of the MAR

In this scenario, corresponding to 20% of the mean annual runoff, both the late summer flood and the freshette permit well developed axial salinity gradients, albeit for short periods of time. As a consequence two periods of maximum recruitment occur, resulting in a mean annual score of 18.

(v) Intermediate runoff scenario : 40% of natural MAR

Additional baseflow in this scenario maintains the axial salinity differences for longer periods of time, providing considerably greater opportunity for recruitment, resulting in a mean annual score of 48.

3.4 Discussion

A biologically meaningful index, which adequately reflects the suitability of freshwater release policies for fish species utilising estuaries, has been described. This index relates the status of the mouth to the presence or absence of the required salinity gradients, and also integrates the extent of dependence of 26 common fish species on estuaries. Since the index integrates our current understanding regarding the key processes, which regulate recruitment into estuaries, we believe that it has the potential to fulfil a vital role in identifying appropriate freshwater release policies for impoundments in South Africa. Although quantitative data to support the findings of these simulations are not available, simulation results are in keeping with the anticipated responses of a reduction in freshwater inflow to estuaries.

We predict that through undertaking additional simulations using a variety of freshwater inflow scenarios it will be possible to define a curve relating freshwater inflow and juvenile marine fish recruitment. As an example, the mean annual fish recruitment indices corresponding to each of the scenarios described above is shown in Figure 6. With a closer assessment of natural fluctuations in freshwater inflow, it would also be possible to define longer term (5 to 10 year) objectives for the management of the estuary for juvenile fish recruitment which includes these natural fluctuations in inflow, and optimise freshwater releases accordingly.

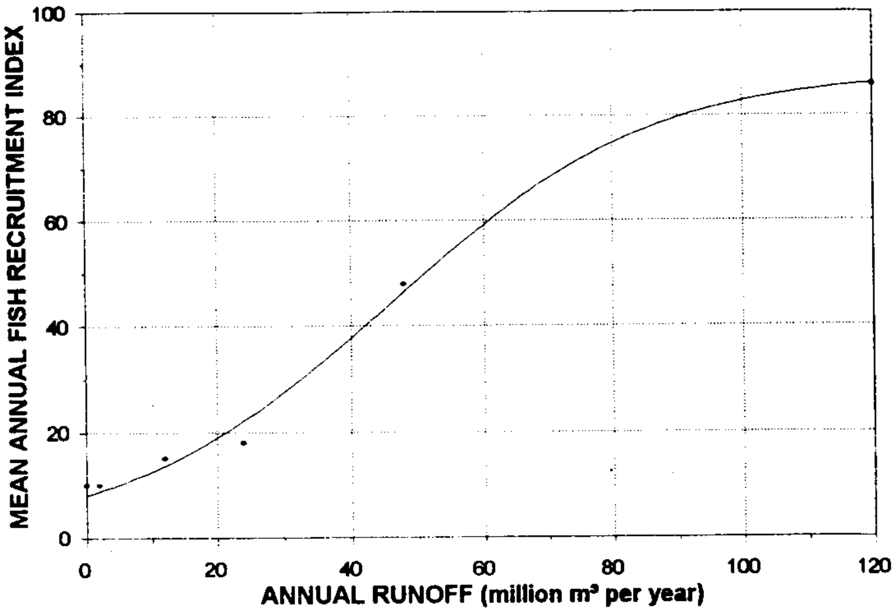


Figure 6: **Summary of several simulations for the Krom estuary showing the relationship between freshwater inflow and performance of the fish** recruitment index

4. CONCLUSIONS

The primary objective of this paper is to demonstrate the value of a decision support system approach to natural resource management. In this case the approach was used to address an estuary management need, and resulted in the formulation of a new estuary management index. In the process, only previously obtained data and understanding was utilised. Given the apparent utility of the index we encourage efforts to link this information to current monitoring programmes with a view to verification of these findings. Further research needs which can be identified as a result of this approach include the identification of the preferred recruitment period for a greater number of fish species and the need to develop a better understanding of the relationship between recruitment processes and axial salinity gradients.

5. ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Water Research Commission for funding this study and to members of the Consortium for Estuarine Research and Management for participating in discussions relating to this research.

See the next three pages for Figure 3 to 5.

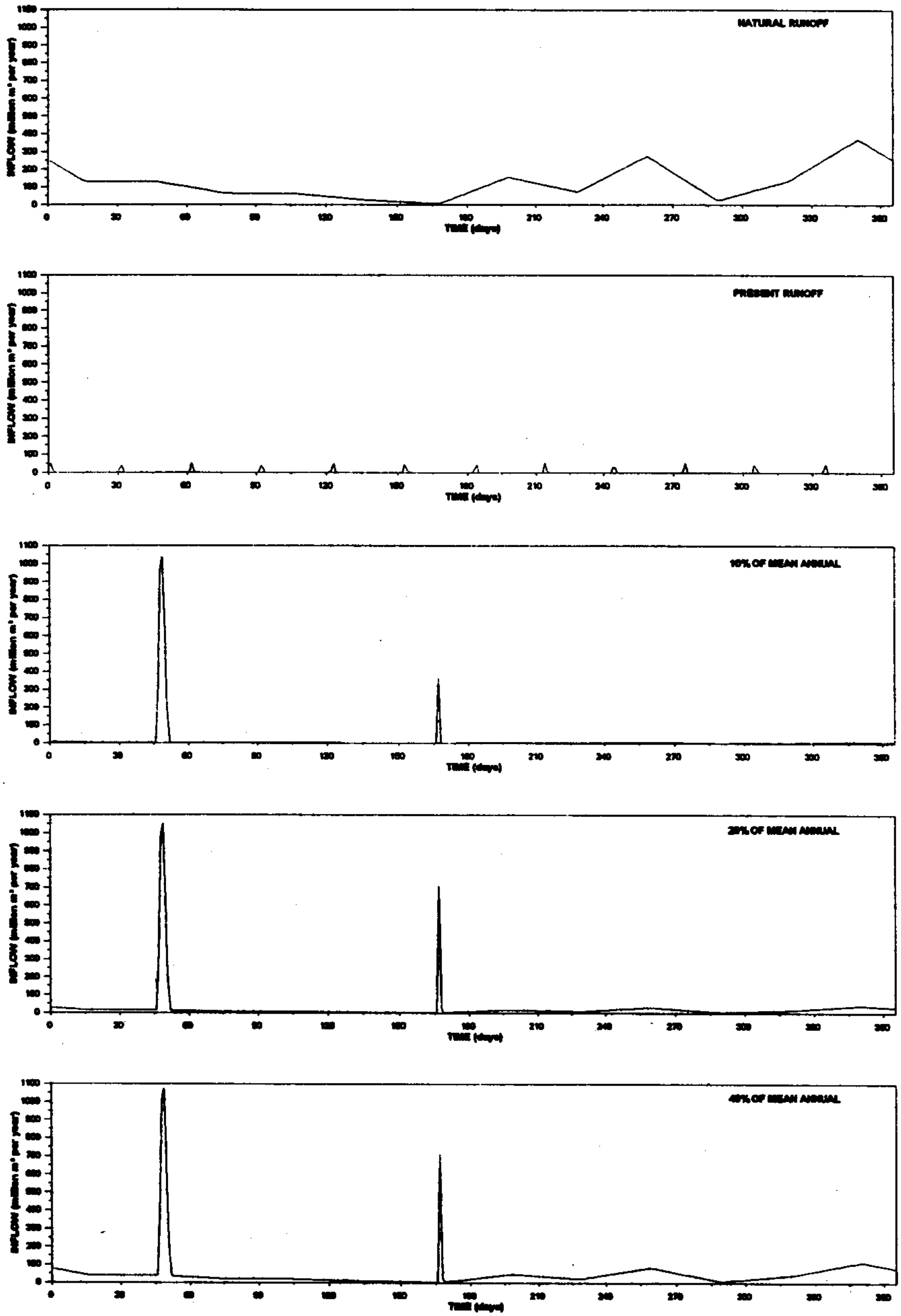


Figure 3: Freshwater inflow scenarios for the Krom estuary

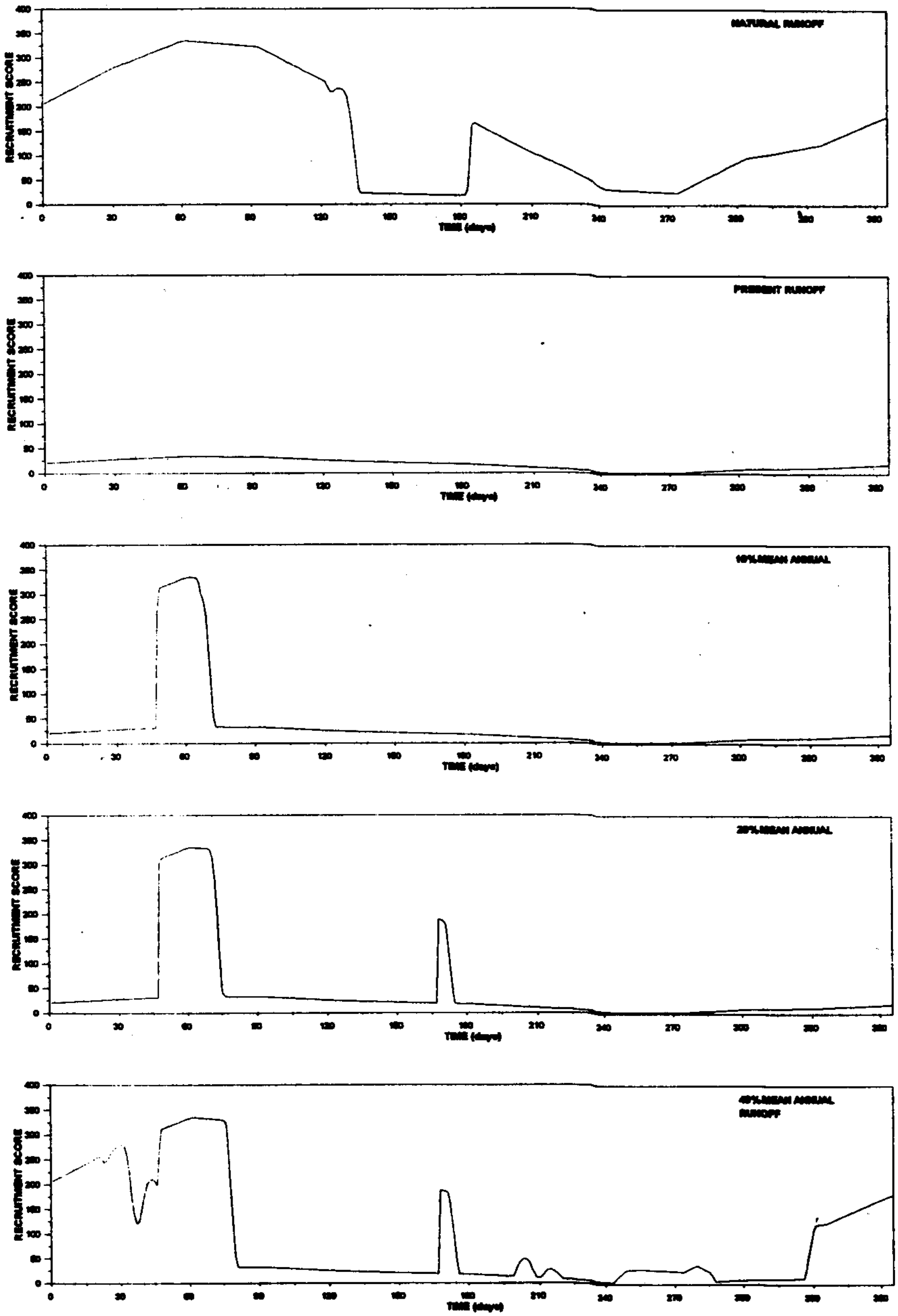


Figure 4: **The fish recruitment score resulting from the 5 freshwater release policies in the Krom estuary**

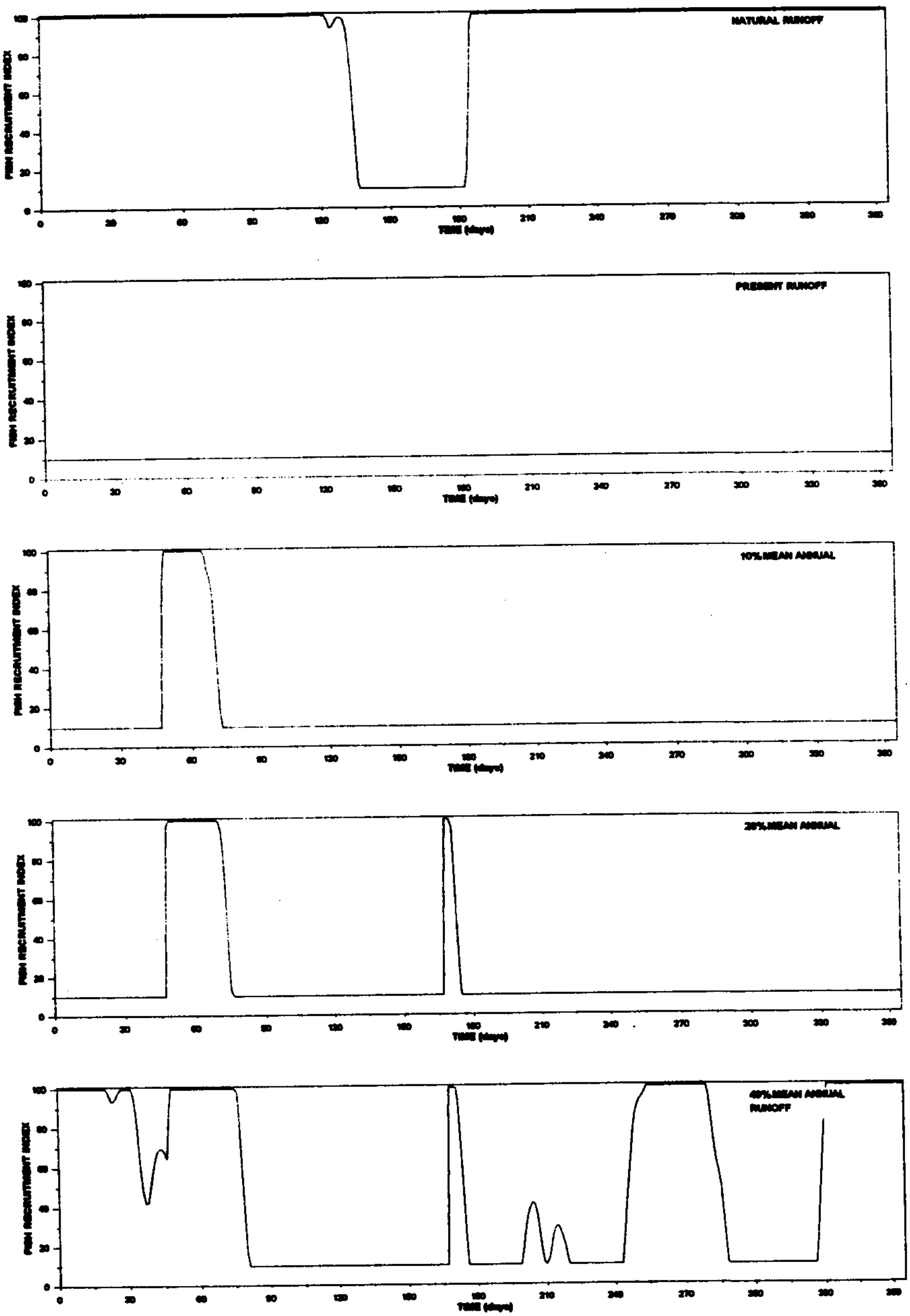


Figure 5: **The fish recruitment index resulting from the 5 freshwater release policies in the Krom estuary**

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