NOTE: All figures are at the end of this document

Fisheries Decision Making and Management Failure: Better Answers Require Better Questions

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Abstract

Many fisheries in North America are in crisis, creating ever more complex problems for managers. Management decisions are contested in court, changed via legislation, or merely ignored. As complexities multiply, accuracy of management predictions decrease. Managers need tools to examine complex fishery systems which include not only biological and economic concerns, but political, social and behavioral responses to decisions as well. To do this non-technical stakeholders must be able to understand and contribute to decision process in a meaningful way. Rather than striving only for better answers, managers must learn to ask better questions. The system dynamics modeling approach has evolved over the past 40 years into a tool widely used for business and policy analysis. Perhaps the time has come for its wider use in fisheries decision making. Qualitative causal loop diagrams, illustrated here, allow clearer thinking about causal links within a system, and provide a first step toward building quantitative, but understandable, “white box” models for fishery decision making.

Introduction

Sophisticated scientific communities dedicated to good fisheries management have often failed to prevent over-fishing even though members of that community, most members of the fishing industry, as well as associated political and governmental entities involved in fishery decision making strive to make reasonable decisions. These decisions have regularly placed management in the unenviable position of trying to protect over-fished stocks while striving to trim back overcapitalized fishing fleets. Many fisheries are seriously over-harvested. Canadian cod fisheries are essentially closed after an unexpected collapse (e.g., Milich 1999; Roy 1996), and North Sea cod stocks are in similar difficulty (Malakoff and Stone 2002). In 2001, the US government determined that 33% of its commercial fish stocks of known status were over-fished (Nmfs 2002). Musick *et al*. (2000) reported that 82 US marine fish species or stocks are vulnerable, threatened, or endangered with extinction from North American waters.

To say that over-fishing is the cause, and less fishing the solution, is insufficient. The more important questions are how did these situations come into being, and how can we correct them? How can our fisheries be rebuilt? While environmental safeguards and habitat protection are important, provision of these will be insufficient without effective management. What appears to be lacking is an effective fishery management system that can sustainably manage fisheries.

Lack of data

Is scientific information lacking? Will more data solve our problems? Probably not. Scientists in developed countries have sophisticated and well funded scientific data collection efforts. Although good data are essential, it is unlikely that additional data alone will lead to significantly better decisions. In fact, some of the best biological and fishery statistical information is associated with those fish stocks (e.g., cod) having the most difficulty. In any case, we can't expect to have perfect knowledge for all fish stocks on a timely basis. In the USA where there are 959 identified commercial fish stocks, sufficient data exist to determine abundance in only about one third of these. In fact, data regarding abundance or fishery status are unavailable for 40% of "major stocks" (NMFS 2002).

Data regarding climate is important and an improved understanding of the effects of climatic mechanisms on fish stocks has been a sub theme in fisheries for many years (e.g., Clark and Hare 2002; Cushing 1982; Jurado-Molina and Livingston 2002). However, incorporating this knowledge into management actions is difficult. Indeed some have accurately pointed out a need for revision of the basic ecological reasoning underlying our fishery management approaches (Rice 2001).

Need for better "management"- application of management science.

Others have examined specific failures in decision making mechanisms, such as the failure to rapidly implement needed restrictions on fishing due to social or economic pressures and the competition among proponents of various approaches and theories. There have been calls for improvement of management's decision making ability so that we might have a more systematic approach to setting and evaluating management objectives, with procedures based on agreed upon decision rules (De La Mare 1998). Lane and Stephenson suggest a better application of management science principles to fisheries issues (Lane and Stephenson 1999).

Uncertainty and risk in management approaches

The need to examine uncertainty in fisheries management has been increasingly recognized by fishery managers since 1990 (Hilborn *et al* 1993). While use of Baysian statistics has improved our ability to understand probable outcomes of management decisions, the incorporation of uncertainty into the management regime is still problematic (Charles 1998; Cochrane 1999; Lane and Stephenson 1998). Uncertainty in stock assessments arises legitimately from climatic variation, for example. Nevertheless, quotas perceived by fishers as "incorrect" can lower compliance with regulations, and can create unfavorable views of management further complicating enforcement (Honneland 2000).

Lauck (1996) investigated the use of hedging as a tool against risk in fishery management, but increasing complexity of fishery management systems conspires to limit its use by fishers. The multiplicity of regulations under complex management regimes can limit fishers' options to counteract uncertainty by preventing them from switching to another fishery (Hilborn R *et al* 2001).

As uncertainty increases, sustainable management requires significantly lowered allowable catches (Walters and Pearse 1996), but these may be politically difficult to implement if economic conditions for fishery participants worsen. Importantly uncertainty also influences the response of fishers to regulation, both in terms of responses to actual regulation as well as response to their perception of possible future regulations (Anderson 1984).

System Complexity

A few researchers have attempted to examine how the complex mixture of biological, social, economic, and environmental information affect the fishery management decision-making process. I believe that these latter workers have pointed the way toward potential answers: The complexities of the fishery and its decision-making system need to be investigated holistically.

The fishery decision-making system is highly complex. Elements of the biological, economic, social, ecological and physical spheres interact via numerous feedbacks. These feedback loops remain largely unexamined during the typical decision making process. Of necessity the decision process focuses on expected benefits via specific decision pathways.

Inevitably unintended consequences arise from these decisions. As catch rates decline, for example, the rate of violation of regulations may increase as fishers try to maximize their ability to pay off debts in a declining industry. Such violations create unreported catches further decreasing the reliability of fishery data which are the basis of future decisions. Declining catches, or certain types of restrictions, also stimulate more effective fishing strategies. These and similar feedbacks conspire to defeat the good intentions of decision makers.

One overriding influence derives from the lag times needed for economic and ecological systems to come into equilibrium, if such equilibrium even exists. Fishery overcapacity develops before over-fishing becomes apparent. Excessive fishing capacity is then supported by economic and associated socio-political concerns. Actions to lower capacity become problematic. If the fishery rebounds additional overcapacity develops (Hennessey and Healey 2000; Ludwig *et al* 1993).

Some suggest that the very complexity of the system contributes to failure. For example, to make fishery regulations more equitable, management may increase special regulations for particular user groups. This makes enforcement more complex and difficult, further increasing non-compliance. As the system becomes more complex uncertainties increase, making desirable outcomes less likely (Healey and Hennessey 1998).

An increasingly complex decision making environment also increases the likelihood of litigation. This causes, at best, significant time lags in imposition of regulations. At worst proposed regulations are reversed causing additional confusion for regulators and fishers. In the USA in the 1970s and 1980s only one or two court challenges were made to NMFS rulings annually, but in the late 90s this rose to more than 10 and in 2001 was over 20 (Gade *et al* 2002).

As (Gade *et al* 2002: xi) state, discussing problems in the USA, "In a real sense, the fisheries management system is in disarray. Management is increasingly exercised by the courts through litigation, by Congress through its annual appropriations and reports, and by constituencies that seek redress through these forums."

Need to Examine overall system complexity

The need to holistically examine fishery systems has been pointed out by several authors in the past. For example Walters (1980) highlighted the importance of viewing fisheries as dynamic systems with interacting biological, political, social and economic components. Anderson, in his discussion of "bioregunomics", specifically included lobbying of fisheries agencies by industry to influence policy, as well as the function of courts as arbiters, as part of a needed new paradigm for fishery management (Anderson 1984; 1987). Recently Charles (1998) structured a book around the concept of fishery systems, and included in that concept management decisions and the response of fishers to them.

Using simulation to compare fishery management systems and procedures is worthwhile in determining the relative utility of various fishery management systems and procedures (e.g. see Cooke 1999; Geromont *et al* 1999; Mcallister *et al* 1999;

Punt and Smith 1999) . While clearly helpful this approach does not explicitly address the many non-management (e.g. political, social and economic) issues that drive feedbacks which influence management success.

It is important to note that fishery management complexity exists not only in terms of detail, but in terms of dynamics. Dynamic complexity arises for many reasons associated with the causal links between components of the system (e.g., see Sterman 2000: 21-22). It is not just that the system is composed of many components, but that a change in one component will cause a complex cycling reaction in many others.

At present fishery management entities are becoming more aware of these problems, and decision makers have extended their analyses beyond bio-economic issues. There is an opportunity to modify management approaches to address issues created by the complexity and uncertainty inherent in the management system. To do this several questions must be answered: How can fishery decision making systems best be analyzed? How can the management system sufficiently account for complexity and uncertainty and still provide meaningful, sufficiently detailed, decisions and policy direction? How can the consequences of management decisions be better examined by inclusion of complex factors beyond the realm of fish population biology?

Using a formal systems perspective to help define complex issues in fisheries

A problem arises in rigorously investigating these systems because there are few standardized techniques available to carry out such holistic studies, particularly if stakeholders from many backgrounds are expected to have some understanding of the issues. One method that is available is the system dynamics approach. Over the past 40 years techniques for the analysis of system structure and dynamics have been refined. Formal approaches for the study of systems emerged as a distinct field within engineering: system dynamics. Subsequently system dynamics has been applied to management science and other fields. Forrester's Industrial Dynamics (Forrester 1961) was probably the first highly detailed application of system dynamics techniques to non-engineering problems. This was later followed by similar studies of urban and world dynamics (Forrester 1969, 1971), and by the well known *Limits to Growth* models (Meadows *et al* 1972; Meadows *et al* 1992). These helped establish system dynamics modeling not only as a means to describe and understand systems, but also as a useful tool in exploring possible scenarios to solve complex real world problems, including those involving human behavior and soft variables.

As it developed technically (e.g., in terms of software availability) the field of System Dynamics also developed what might be called a philosophical approach toward model building. System dynamics practitioners admit from the start that "all decisions are based on models … and all models are wrong," (Sterman 2002) and that modeling should be carried out in a reflective and cooperative mode. Models should be understandable to as wide an audience of stakeholders as possible. This promotes, among other things, a cooperative approach toward model building, and an increased ownership of the models, and outcomes, by clients.

Causal loop diagrams can be considered a sub-set of the system dynamics paradigm. They are a rigorous but qualitative approach for looking at complex issues involving feedback systems (see Sterman 2000, chapter 5 for a discussion of this approach). If simple, causal loop diagrams (CLDs) may be useful in examining outcomes and providing general advice. However, CLDs cannot be used for detailed analysis. Even relatively simple feedback systems are too complex for, even thoughtful, visual analysis. There are also some significant problems in using CLDs without building quantified models (See Richardson (1986; 1997) for a discussion of weaknesses of CLDs). On the other hand CLDs do provide an ideal framework for defining problems, and for establishing a basis for logical discussion of these problems. CLDs also provide a valuable first step toward development of quantified system dynamics models of the problem to be solved: our current difficulties in fishery management.[1]

The following presents, in increasingly complex CLD format, some of the intertwined management problems facing fishery managers. The purpose of this is to illustrate the types of things that might be considered in building a system dynamic model of a fishery management system including political and socio-economic considerations.

The Basic Management Scenario

The first CLD (Figure 1) illustrates the core of the management system as seen by traditional fishery managers. As the *amount of fishery resource*[2] drops, the *estimated amount of fishery resource* will also drop causing an increase in the *gap between the desired and estimated resource levels*. As this gap increases the *planned allowable catch* will decrease causing a decrease in the *allowable catch* other things being equal. Decrease in *allowable catch* will decrease the *amount of fishing* and thus the *fish harvest*, causing an increase in the *amount of fishery resource*. This loop illustrates a negative feedback or stabilizing aspect of our system. However, it is important to point out that there are explicit time delays indicated by the boxed model components (which would become stocks, or state variables, in a quantified model). Time delays can substantially alter the behavior of the system and, even in a simple negative feedback system, can cause system oscillations. Also shown are the fact that allowable catch is determined by planned allowable catch as modified by *political pressure for higher catch rates* and ability to implement needed conservation measures

Additional loops modify this structure. If the *gap between desired and estimated resource* becomes very large there is an increasing *risk to the future resource* and the *need for emergency fishery limitations* grows, precipitating additional decreases in the *planned allowable catch*. We also know that as the *amount of fishing* grows there

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[1] Readers may wish to examine a simple quantified system dynamics model which was presented at the AFS annual meeting in 1999 by the author: Dudley, R. G. and Chris S. Soderquist. 1999. A simple example of how system dynamics modeling can clarify, and improve discussion and modification, of Model Structure. (A written version is available at: www.people.cornell.edu/pages/rgd6/dudspbs.html).

[2] In keeping with the SD philosophy of creating understandable models I have used descriptive variable names. In the text I have indicated these in italics.

may be increasing *indirect damage to the resource base* which will cause a decrease in the *amount of fishery resource* not caused by the *fish harvest* itself. Here we may think of damage from trawling, by-catch, or alterations to food webs, for example. Additional feedbacks connect the *amount of fishery resource* and *fish harvest*, and the *amount of fishery resource* to its own *growth, reproduction and deaths*. This latter loop is indicated with unsigned arrows partly because there are several imbedded feedbacks beyond our discussion here, and also because I wish to emphasize fishery management decision dynamics not population dynamics.

At this stage in the CLD building exercise, amount of fishery resource is affected by 6 feedback loops (Figure 1.

Adding Fishing Industry Infrastructure

The *fish harvest* itself, as well as the *estimated amount of fishery resource*, combine to create a *perceived amount of fishery resource*. If the *value of fish* is sufficient then industry participants' *perceived benefits of fishing* will increase stimulating more *investing in fishing industry* which increases the *established industry infrastructure*. This will cause the *desired amount of fishing to rise*, and will result in more fishing, and a higher *fish harvest*. As long as fish harvests remain high the fishery continues to grow, a positive feedback loop … other thing being equal (Figure 2).

Eventually, the *amount of fishery resource* drops, limiting *fish harvest* directly. The dropping *amount of fishery resource* also influences the basic management loop in such a way as to limit the *amount of fishing* unless the *desired amount of fishing* increases *political pressure for higher catch rates* enough to sufficiently increase *allowable catch*. The system rapidly gets more complex. At this stage of model building *amount of fishery resource* is affected by 12 feedback loops (Figure 2).

Adding Debt

As investments are made debt is also acquired, and this needs to be paid off by catching fish. This is illustrated by adding the debt loop (Figure 3). Investing in fishing industry infrastructure increases the *amount of debt* which creates a larger *need to pay back debt*. Because fishing is usually the means by which debt is paid back, the result is a greater *desired amount of fishing* as debt increases. This increases *amount of fishing*, and, depending on the circumstances, increases *political pressure for higher catch rates* as well.

Depending on the fishery resource situation, increases in *amount of fishing* may reduce debt or may increase it. This is because increasing *amount of fishing* could increase *amount of debt* if money is borrowed, for example, for fuel, repairs and other operating expenses. If *fish harvest* is sufficiently high then these costs will be covered by the value of the catches and other debt might also be paid back.

The addition of the debt loop increases the number of feedback loops affecting the *amount of fishery resource* to 20.

Incorporating Scientific Advice

Because fishery management decisions depend on data from the fishery, the issues illustrated in Figure 4 are also relevant. If *confidence in scientific advice about the resource* is weakened then there is less *ability to reach consensus about the resource status*. If *enforcement effectiveness* is also weak then failure to reach a strong consensus will tend to increase the *amount of illegal fishing* (or under-reporting of catch, etc.) limiting the *accuracy of fishery based data*. This ultimately results in a further degradation of *confidence in scientific advice about the resource*. This positive feedback will be reinforced if there are significant *ecological uncertainties* that also limit the accuracy of scientific advice. The ecological effects will be exaggerated in cases where the stock size is low, because under such conditions the destabilizing effects of reproductive variability are increased.

Importantly, low *confidence in scientific advice about the resource* and an in*ability to reach a consensus about resource status* will weaken the *ability to implement needed conservation measures*. Under conditions when *desired amount of fishing* (Figure 4) is high this could lead to severe over-fishing. Such a deteriorating situation could also be brought about by contentious court cases and other disagreements among stakeholders. One lesson we might learn, is that contestants in such disagreements should strive to solve differences cooperatively to reinforce the confidence in scientific advice. Or similarly, as is happening now, agencies should work doubly hard to explain uncertainties so that fishers and co-administrators will realize that there is a range of possible outcomes from a specific decision.
There may be a need for additional loops like this representing other political and user group feedbacks. One may wish, for example, to include effects of apparent inaccurate predictions on the budget size of a particular fisheries research agency, which then might be denied the funds to make good predictions.

The big picture

Figure 5 combines information presented in Figure 3 with that from Figure 4. Some other additions have been made. A three step feedback is shown leading from *amount of fishery resource* to *accuracy of predictions*. This represents the idea that a decrease in the *relative size of the actual fish stock* tends to increase *fluctuations in reproduction* (in comparison to stock size). This tends to make predictions less accurate, in relative terms, just when they need to be more accurate. This effect can be made more severe by *ecological uncertainties* which also have (here unspecified) effects on *growth and reproduction*. As *accuracy of predictions* decreases *confidence in scientific advice about the resource* will also decrease. Decreasing accuracy of prediction also has important effects, which may be positive or negative,[3] on the *estimated amount of fishery resource*.

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[3] Typically causal loop diagrams require that arrows connecting model components are given some indication of direction of change, e.g., a "+" or "–" sign. Because I have opted to eliminate additional complexities, some arrows (shown with broken lines) do not have such polarity. Such connections are more complex than indicated here.

Another small, but important, loop links the *amount of fishery resource* to the *level of technology used* in fishing. If the amount of fishery resource declines, fish become more difficult to catch, resulting in an increasing *level of technology used* in fishing.[4] Omitted here is the feedback from *level of technology used* to the *accuracy of predictions*. If changes in technology are not known to those analyzing data then inaccuracies in the fishery analysis will increase.

An additional feedback (bottom of Figure 5) captures the idea that a decreasing allowable catch will increase *fishers' perception of risk to future harvests* (even though such decreases are designed to protect future harvests). This will tend to increase the *need for fishers to have a short term view* of resource exploitation and will decrease the *ability to implement needed conservation measures*.

Of course this big picture is incomplete. I have lumped all issues related to *growth and reproduction* in one component. I have ignored species interactions except to include them in *ecological uncertainties*. A complete analysis would explicitly include delays in decision making. Recognizing the inadequacies of this representation of realities facing fishery managers, the complexity of the problems is still startling. Consider that the description in **Error! Reference source not found.** is already rather complex in terms of feedback. *Amount of fishery resource* is a component of over 100 feedback loops. *Accuracy of predictions*, in spite of the omission of numerous items, is a component in 65 loops. *Allowable catch* is a component in 79. Given the complexity of these feedbacks could we predict the effect of an increase of 10% in *allowable catch*, even in the absence of ecological uncertainties? Can we understand the effects that might accompany a decrease of 15% in *enforcement effectiveness*?

Conclusion

Depending on specific values in a possible quantified model based on the above structure, the system as outlined here may oscillate, even if no random components are included and we ignore biological and ecological components. That is, the structure of the system will probably generate oscillations; there may be no equilibrium values. The well know example of repeated development of overcapacity in a fishery, which then drops back as stocks collapse (Hennessey and Healey 2000; Ludwig *et al* 1993) is one example. True equilibrium in our fisheries may be rare.

Clearly the current management system is in crisis despite the good intentions of most players. Innovative approaches are needed to examine these problems. We need to be interested, not only in obtaining better data about specific fisheries, but in a

[4] Normally we should be able to word these comments in the opposite way: "As the *amount of fishery resource* <u>rises</u> fish become <u>less</u> difficult to catch resulting in a <u>de</u>creasing *level of technology used* in fishing …" etc. In this, and some other cases, this is not strictly valid, exposing one of the weaknesses of CLDs. Here, in a quantified model, *level of technology used* would be modeled as a stock with an inflow of "changing fishing technology". This stock 'level of technology used' would increase when *amount of fishery resource* is low, but would not dissipate rapidly if *amount of fishery resource* rose again. In other words increases in fishing technology tend to be relatively permanent, if they are useful, regardless of subsequent increases in stock size.

creating a better understanding about how our fishery systems work, and how they can be improved. If we wish to improve the management results, it may be necessary to use quantified versions of models similar in structure to that outlined here. Then we might investigate what feedbacks in the system are most problematic. If these were identified (and they may not even be in the current model) various corrective policies could be investigated. Means of reducing the complexity, at least in the social, economic and political parts of our system, might also be discovered. Most importantly, such an approach allows us to ask better questions.

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Figures:

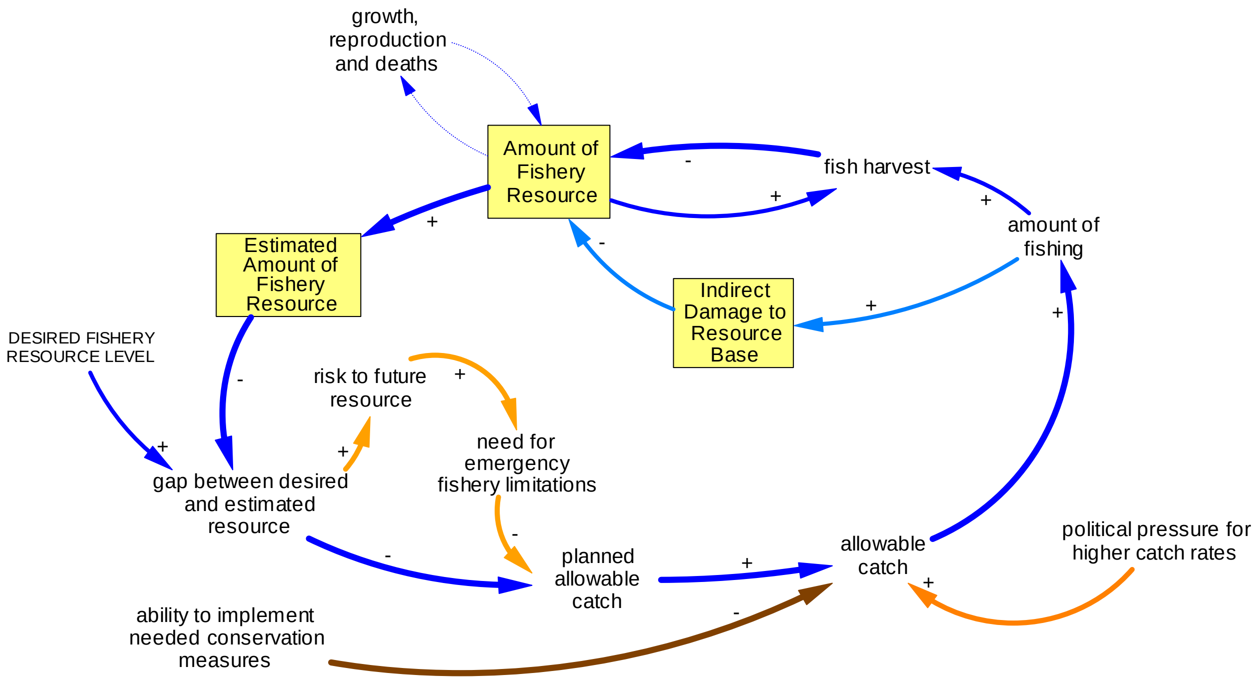

Figure 1. A causal loop structure which describes the basic situation of fishery managers. The polarity on each arrow indicates the direction of change in the second component of a pair given a change in the first component. Thus a "+" sign indicates that the second component of a pair will change in the same direction as the first. A negative sign implies a change in the opposite direction. In "reading" these pair-wise relations we always subconsciously add the phrase "other things being equal, which of course they are not." Thus we can say: "as the amount of fishing increases the fish harvest will also increase, other things being equal…." Of course we also know that fish harvest will also depend on the amount of fishery resource. The shape of the pair-wise relationships is not indicated in CLDs.

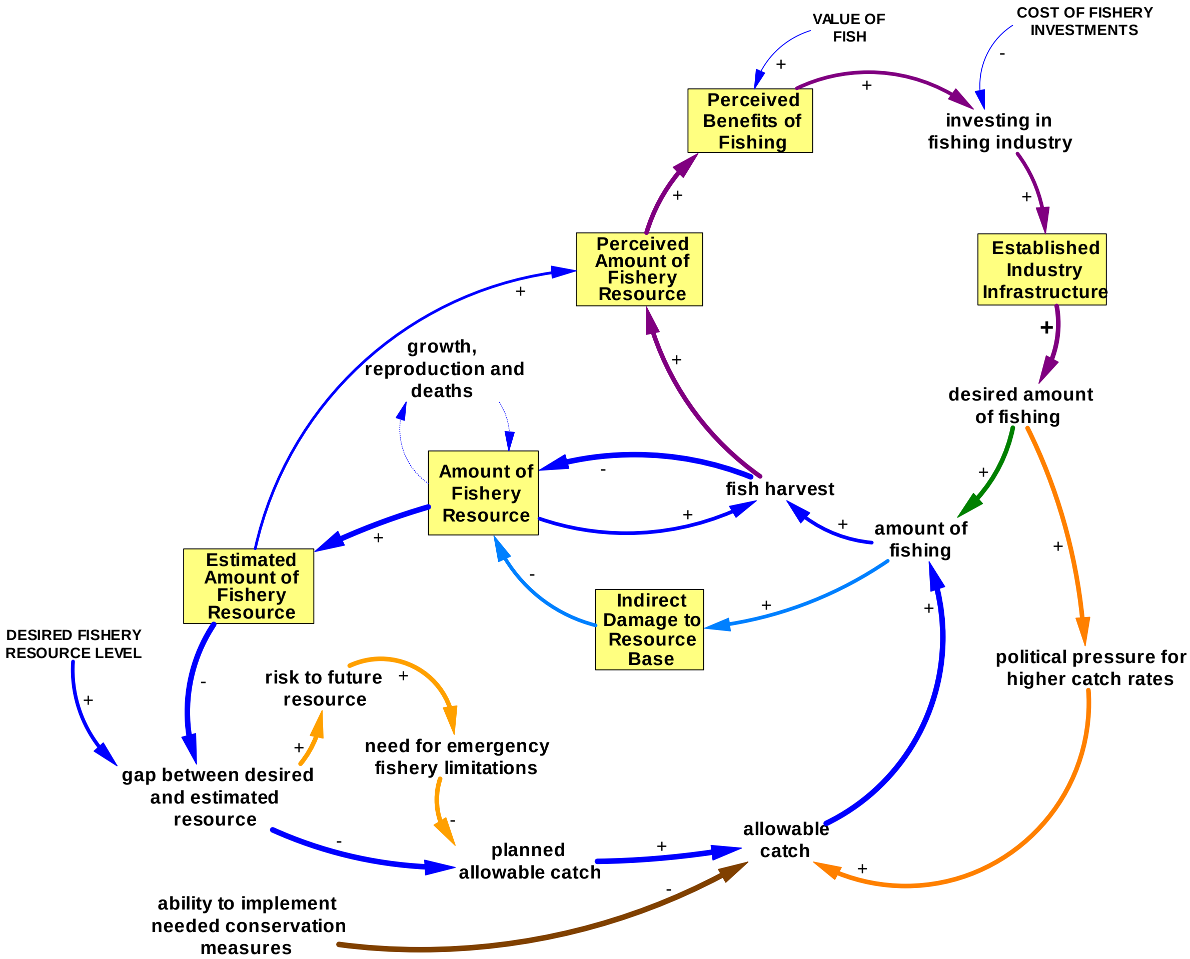

Figure 2 The addition of fishery industry infrastructure to the CLD adds complexity to the management problems.

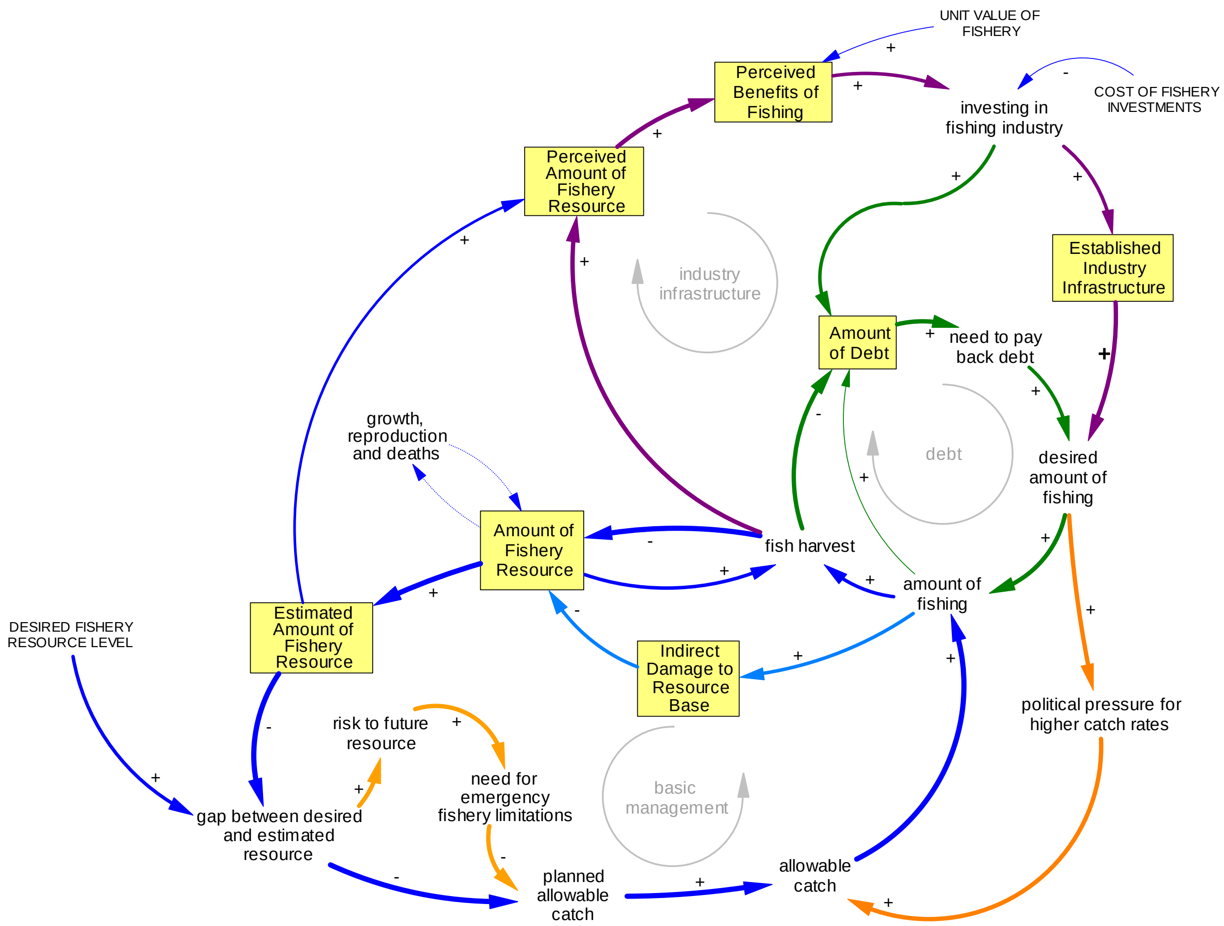

Figure 3. The addition of the debt loop adds further complexity. At this stage there are 20 feedback loops affecting *amount of fishery resource*.

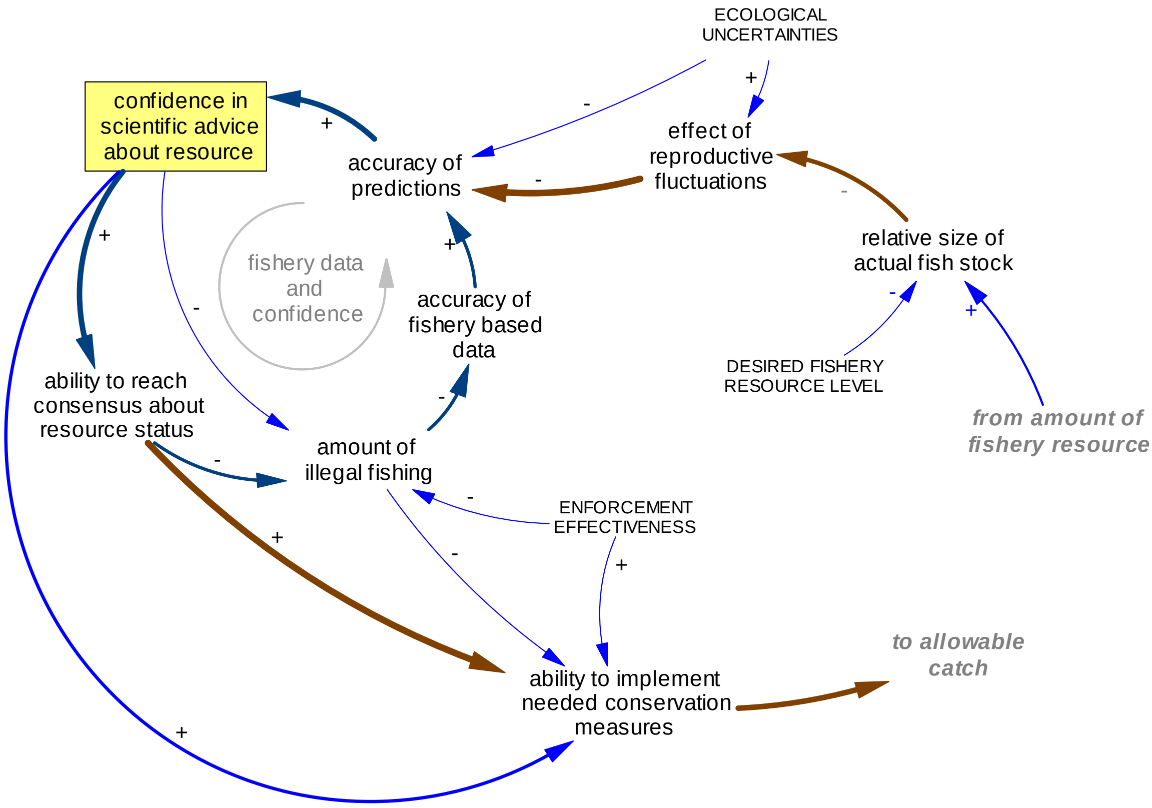

Figure 4. Issues related to scientific advice and management decision making cause additional complexity.

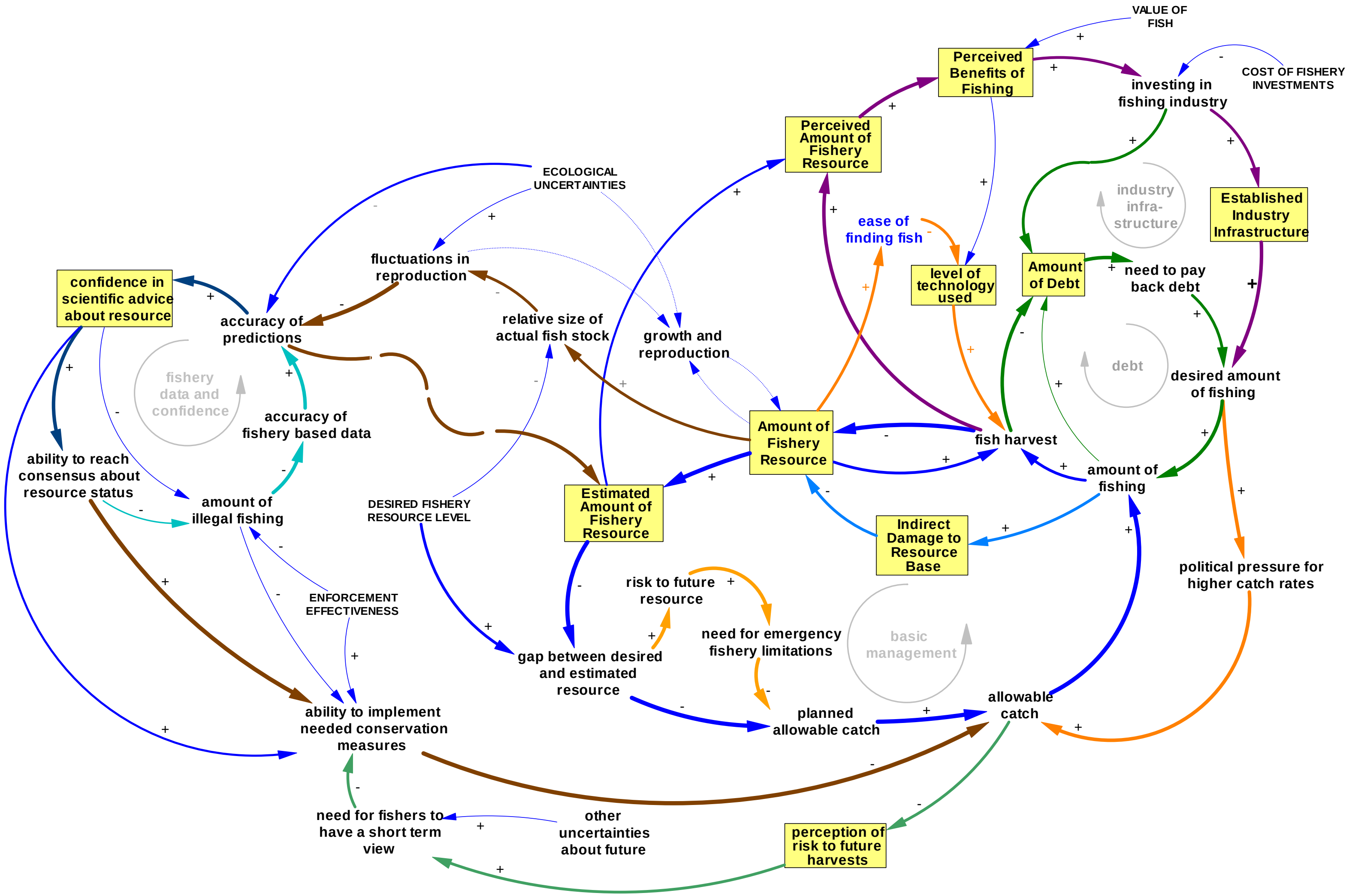

Figure 5. This figure combines information from Figure 3 and Figure 4 and represents a highly simplified version of feedbacks affecting fishery management decision making. Nevertheless, as diagramed here, *amount of fishery resource* is a component in over 100 feedback loops. The inherent complexity of the fishery management system limits our ability to understand and manage our fisheries successfully. However, quantified system dynamics models, based on causal loop diagrams like that shown here, can be constructed to examine and analyze this type of complexity.