CHAPTER 1
An introduction to environmental flows

Summary

Environmental flows are flows in a river required to sustain aquatic ecosystems and other beneficial uses of free-flowing rivers. Environmental flow assessment is a general term for studies that can inform management of flows. Such assessments are surprisingly difficult to do right, constrained by the natural variability of the environment through which rivers flow and the diverse needs of organisms that live there. They are also made difficult by social constraints that pit human demands for water against those of the environment, and by aspects of human behavior.

1.1 What are environmental flows?

The 2007 Brisbane Declaration of the 10th International River Symposium and Environmental Flows Conference states that: “Environmental flows describes the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend upon those ecosystems.” We will use this definition, taking “freshwater ecosystems” to include riparian areas. “Instream flows” is an older term that means much the same thing, but we prefer “environmental flows” because it implies a broader view of what should be assessed; instream flow assessments historically have been concerned mainly with the physical environment of only a few species, especially salmonids. We take environmental flow assessment (EFA) to be the process of trying to translate the Brisbane definition into usefully precise estimates of environmental water needs and the effects of modified flows on ecosystems and human well-being, to inform decisions such as:

- Whether to reserve some portion of the flow in a stream for environmental uses, and if so, how much, and on what kind of schedule;
- How effects of an existing project on streams or estuaries can be mitigated (or not) by releases of environmental flows or restrictions on water withdrawals;
- Whether and how to modify existing water projects to improve environmental conditions;
- Whether and how to build a new water project.

Environmental flow assessment is hard to do well. This book is about the scientific and social difficulties with EFA and how to address them as best one can. In this chapter, we first explain why EFA is so difficult, and address problems with the EFA literature.
1.2 Why EFA is so hard; scientific issues

1.2.1 Stream ecosystems are dynamic and open

Twenty-some years ago, three of the authors of this book participated in a small workshop on environmental flow assessment at the University of California at Davis, which concluded that “…currently no scientifically defensible method exists for defining the instream flows needed to protect particular species of fish or aquatic ecosystems” (Castleberry et al. 1996). Despite major progress with analytical and statistical methods over the last 20 years, especially those described in Chapter 9, we still believe that at best an EFA should be regarded as a first cut, to be implemented within the context of adaptive management. Why is this problem so hard? Scientists have a truly wonderful understanding of the nature of energy and matter, the evolution of the universe, the atomic structure and properties of molecules, the structure and activities of cells, the origin of species and the evolutionary relationships among organisms, and much more. Why, then, is it so hard to assess the consequences of taking some of the water out of a stream, or changing the timing or temperature with which water flows down the stream?

The reasons have been known for some time: ecosystems are open, dynamic systems that are “…in a constant state of flux, usually without long-term stability, and affected by a series of human and other, often stochastic, factors, many originating outside of the ecosystem itself” (Mangel et al. 1996, p. 356). For such reasons, Healey (1998) argues that questions such as “How much can a river’s hydrology be altered without endangering its ecological integrity?” are trans-scientific, sensu Weinberg (1972); trans-scientific questions: “… can be stated in the language of science but not answered by the traditional means of science.” These ideas have been restated recently by Harris and Heathwaite (2012) and by Boyd (2012, p. 307): “Predicting the dynamics of real ecosystems – or even of components of these ecosystems – will remain beyond the reach of even the best ecosystem models for the foreseeable future.”

A long-term study on the South Fork Eel River in Northern California (Box 1.1) illustrates these points. Although the highly predictable seasonality of flow is a major factor structuring the food web in that river, year-to-year variation in the timing and magnitude of high-flow events results in substantial variation in the structure of the food web and its response to mobilization of the bed by high flows; for practical purposes, predictions of the response can only be probabilistic, not deterministic.

As another example, consider the valuable and well-managed sockeye salmon fishery in Bristol Bay, Alaska, for which long-term catch records are available for three major fishing districts, corresponding to areas of spawning and rearing habitat. The catch is a good proxy for the number of spawning fish, known since about 1950 (Hilborn et al. 2003). Although there has been little human disturbance in the spawning and rearing areas except for climate change, the relative contributions to the catch from the different districts has varied widely over time, as described by Hilborn et al. (2003, p. 6567):

The stability and sustainability of Bristol Bay sockeye salmon have been greatly influenced by different populations performing well at different times during the last century. Indeed, no one associated with the fishery in the 1950s and 1960s could have imagined that Egegik would produce over 20 million fish in 1 year, nor could they imagine that the Nushagak would produce more than the Kvichak, as it has in the last 4 years. It appears that the resilience of Bristol Bay sockeye is due in large part to the maintenance of all of the diverse life history strategies and geographic locations that comprise the stock. At different times, different geographic regions and different life history strategies have been the major producers. If managers in earlier times had decided to focus management on the most productive runs at the time and had neglected the less productive runs, the biocomplexity that later proved important could have been lost.

Hilborn et al. (2003) were thinking of fisheries management, but the same point would apply to
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Managing the freshwater habitat in these regions; there have been major geographical shifts in productivity in this undisturbed habitat, and no one knows why.

1.2.2 Fish evolve

We are used to thinking of evolution as a slow process, but this is not always the case. Stearns and Hendry (2004) wrote that: “A major shift in evolutionary biology in the last quarter century is due to the insight that evolution can be very rapid when populations containing ample genetic variation encounter strong selection (citations omitted).” It is now clear that significant evolution can occur within the time spans commonly considered in EFA, and fish populations may respond to changes in the environment in unexpected ways. For example, in several California rivers, releases of cold water from the lower levels of reservoirs have created have good habitat for large trout. The steelhead populations in these rivers apparently have evolved toward a resident life-history in response (Williams 2006). Where hatcheries “mitigate” for habitat lost above dams, salmonids evolve greater fitness for reproduction in hatcheries, and lower fitness for reproducing in rivers (Myers et al. 2004; Araki et al. 2007; Christie et al. 2014); significant domestication can occur in

Box 1.1 Variable Effects of High Flows on a River Ecosystem

Eighteen years of field observations and five summer field experiments in a coastal California river suggest that hydrologic regimes influence algal blooms and the impacts of fish on algae, cyanobacteria, invertebrates, and small vertebrates. In this Mediterranean climate, rainy winters precede the biologically active summer low-flow season. *Cladophora glomerata*, the filamentous green alga that dominates primary producer biomass during summer, reaches peak biomass during late spring or early summer. *Cladophora* blooms are larger if floods during the preceding winter attained or exceeded “bankfull discharge” (sufficient to mobilize much of the river bed, estimated at 120 m³ s⁻¹). In 9 out of 12 summers preceded by large bed-scouring floods, the average peak height of attached *Cladophora* turfs equaled or exceeded 50 cm. In five out of six years when flows remained below bankfull, *Cladophora* biomass peaked at lower levels. Flood effects on algae were partially mediated through impacts on consumers in food webs. In three experiments [with caged fish] that followed scouring winter floods, juvenile steelhead (*Oncorhynchus mykiss*) and ...[coastal roach, *Hesperoleucus venustus*] suppressed certain insects and fish fry, affecting persistence or accrual of algae depending on the predator-specific vulnerabilities of primary consumers [that were] capable of suppressing algae during a given year. During two post-flood years, these grazers were more vulnerable to small predators (odonates and fish fry, which... [steelhead stocked in the cages always suppressed] ... [As a result, the abundant grazers] had adverse effects on algae in those years. During one post-flood year, all enclosed grazers capable of suppressing algae were consumed by steelhead, which therefore had positive effects on algae. During drought years, when no bed-scouring winter flows occurred, large armored caddisflies (*Dicosmoecus gilvipes*) were more abundant during the subsequent summer. In drought-year experiments, stocked fish had little or no influence on algal standing crops, which increased only when *Dicosmoecus* were removed from enclosures. Flood scour, by suppressing invulnerable grazers, set the stage for fish-mediated effects on algae in this river food web. Whether these effects were positive or negative depended on the predator-specific vulnerabilities of primary consumers that dominated during a given summer. (Power et al. 2008, p. 263 edited for clarity)
a single generation (Christie et al. 2016). If hatchery fish mix with naturally spawning fish in the river below the dam, the population of naturally spawning fish below the dam that can be supported by a given flow regime will be reduced as fitness declines.

1.2.3 Streams adjust
Alluvial or partially alluvial streams create their own channels. Anything that substantially changes flow or sediment transport in a stream, such as a new dam, will provoke geomorphic adjustments in channel size and form that will change the physical habitat, compromising assessments based on the pre-project habitat.

1.2.4 Climate changes
Long-term climate records and paleoclimatic data from tree rings and other sources show that climates have always varied over decades and centuries, and now greenhouse gas emissions are driving rapid change. One predictable change, already evident in flow data, is more winter runoff and less snowmelt runoff in mountain streams. Precipitation may increase or decrease, depending upon the region, and may become more variable. Thus, the amount and temporal distribution of water available to be allocated between instream and consumptive uses will change, as will the temperature of the water. Methodologically, climate change confounds analytical methods that assume that the statistical properties of flow data will be stationary, i.e. not change over time (Milly et al. 2008). Predicting climate change at any particular location is even more difficult than predicting global change (Deser et al. 2012), so uncertainty about climate will add substantially to the uncertainties already faced in EFAs.

Even without major human influences, climates and flow regimes vary substantially over time, especially in arid and semi-arid regions, as shown by a plot of the 30-year running average discharge in the Arroyo Seco River in California. (Figure 1.1). Thus, the particular period of record that is available for analysis can make a major difference (Williams 2017). Probably the most famous example of this is the Colorado River Compact of 1922, which allocated the water from the Colorado River among the various states of the USA in the basin. The allocation was based on unusually high flows in the early twentieth century, and so seriously over-allocated water from the river, as noted by the National Research Council (2007, pp. 99, 103):

![Figure 1.1](image_url)  
**Figure 1.1** Thirty-year running average discharge in the Arroyo Seco River in central California. There has been no significant development in the basin. Data from the USGS gage 11152000. Source: John Williams.
From the vantage point of the early 21st century, there is now a greater appreciation that the roughly 100 years of flow data within the Lees Ferry gage record represents a relatively small window of time of a system that is known to fluctuate considerably on scales of decades and centuries. (p. 99). … Long-term Colorado River mean flows calculated over these periods of hundreds of years are significantly lower than both the mean of the Lees Ferry gage record upon which the Colorado River Compact was based and the full 20th century gage record (citation).

1.2.5 Populations vary
Populations of fish and other aquatic organisms can be highly variable in time and space (e.g. Dauwalter et al. 2009), even in stable stream environments (e.g. Elliott 1994). This makes it hard to determine population trends or whether changes in flows have done any good or harm (Korman and Higgins 1997; Williams et al. 1999). This is particularly true for anadromous fish, populations of which may be strongly affected by ocean conditions that vary from year to year (e.g. Lindley et al. 2009). Within short sections of streams, abundance can vary strongly over periods of days (e.g. Bélanger and Rodríguez 2002), so assessments of habitat quality based on fish density can be unstable.

1.2.6 Habitat selection is conditional
Environmental flow assessments are often based on the assumptions that providing more of the kind of habitat where fish are found will increase the population of fish. The assumption may be sound, provided that it is tempered by biological understanding, by appropriate choice of spatial scale in the assessment, and by the recognition that habitat selection is conditional; in other words, fish can only select habitat that is available to them, and habitat selection at fine spatial scales can be affected by many factors, including habitat at coarser spatial scales, population density, competition, season, water temperature, cloud cover, and even discharge (Chapter 7). It is also necessary to consider how much of a particular kind of habitat a population of a given size needs, and to recognize that other factors altogether may determine abundance. Habitats affect populations through their effects on births, deaths, growth, and migration.

1.2.7 Spatial and temporal scales matter
The response times of the resources of concern complicate EFAs. Biotic communities may take decades to respond detectably to management actions, or the response may change over time. For example, the population of Sacramento River spring Chinook salmon initially increased after the construction of Shasta Dam (Eicher 1976), but later collapsed (Williams 2006), probably because of interbreeding with fall Chinook salmon. This problem is particularly acute for fish that use spatially dispersed and distinct habitats over the course of their life cycles, when only some of the habitats are affected by the actions.

Even if the inquiry concerns physical habitat, response times may still present problems. Events such as scouring floods that seem to destroy habitat in the short term may create other habitat, such as deep pools, in the long term. Anything that substantially changes sediment transport in a stream, such as a new dam that blocks sediment transport or modifies flows, will provoke geomorphic adjustments in channel size and form that will change the physical habitat.

Spatial scales also matter, for example in assessments of habitat selection (Cooper et al. 1998; Welsh and Perry 1998; Tullos et al. 2016). Factors that seem to drive habitat selection at a fine spatial scale may explain relatively little at a coarser spatial scale (Fausch et al. 2002; Durance et al. 2006; Bouchard and Boisclair 2008). As an additional complication, organisms can select habitat at multiple scales. In a classic observational study, Bachman (1984, p. 9) wrote that:

The mean home-range size of 53 wild brown trout was 15.6 m² (SE, 1.7) as determined from minimum-convex polygons encompassing 95% of the scan sighting of each fish each year. … Typically, foraging sites were in front of a submerged rock, or on top of but on the downward-sloping rear surface of a rock.
… From there the fish had an unobstructed view of oncoming drift. While a wild brown trout was in such a site, its tail beat was minimal … indicating that little effort was required to maintain a stationary position even though the current only millimeters overhead was as high as 60–70 cm s\(^{-1}\). Most brown trout could be found in one of several such sites day after day, and it was not uncommon to find a fish using many of the same sites for three consecutive years.

Thus, the trout selected habitat on a scale of centimeters with respect to the rock, on a scale of meters with respect to incoming drift, and a scale of tens of meters with respect to home range; further study might have shown selection of home ranges on a scale of hundreds or thousands of meters.

1.3 Why EFA is so hard: social issues

1.3.1 Social objectives evolve
Like ecosystems, societies are not stable equilibrium systems; social attitudes and objectives also evolve, as do environmental laws and regulations, and the evolution is rapid relative to the duration of major water-development projects. We are old enough to remember the resurgence of environmental concern in the 1960s that laid the basis for much of current environmental law in the USA, such as the Clean Water Act, the Endangered Species Act, and the National Environmental Policy Act. Environmental concerns also affected judicial decisions. For example, in 1971, in *Marks v. Whitney* (6 Cal.3d 251), a decision about tidelands in Tomales Bay, the California Supreme Court broadened the uses that are protected by the Public Trust to include providing environments for birds and marine life, and scientific study. This decision did not come from abstract legal reasoning, but rather from the political mood of the time. In pertinent part, the decision states that:

> Public trust easements are traditionally defined in terms of navigation, commerce and fisheries. They have been held to include the right to fish, hunt, bathe, swim, to use for boating and general recreation purposes the navigable waters of the state, and to use the bottom of the navigable waters for anchoring, standing, or other purposes (citations omitted). The public has the same rights in and to tidelands. … The public uses to which tidelands are subject are sufficiently flexible to encompass changing public needs. In administering the trust the state is not burdened with an outmoded classification favoring one mode of utilization over another (citations omitted). There is a growing public recognition that one of the most important public uses of tidelands – a use encompassed within the tidelands trust – is the preservation of those lands in their natural state, so that they may serve as units for scientific study, as open space, and as environments which produce food and habitat for birds and marine life, and which favorably affect the scenery and climate of the area. …

This broadening of trust uses was extended to navigable lakes and streams and their tributaries in 1983 in *National Audubon Society v. Superior Court* (33 Cal.3d 419), concerning environmental flows in Rush Creek, a tributary to Mono Lake. The Audubon decision and the environmental attitudes it reflected also gave new life to existing legislation affecting environmental flows, such as Fish and Game Code sec. 5937, discussed in Chapter 2. Changing social attitudes also change the practical effect of environmental laws. Monticello Dam on Putah Creek in California releases water for re-diversion 10 km downstream. These releases support a trout fishery, which, together with recreational uses of the reservoir, was long thought to meet any environmental obligations arising from the project, including Fish and Game Code sec. 5937. Over time, however, native fishes that were formerly regarded as “trash fish” came to be valued, and litigation resulted in revised environmental flow releases to protect them (Moyle et al. 1998).

Similar changes have developed elsewhere, although the nature and pace of the change has varied among nations and regions. South Africa, for example, experienced sudden advances in the relevant law and methods for EFA in the euphoric period after Nelson Mandela ushered in a peaceful end to
apartheid. Together with scientists in Australia, where semi-arid conditions made methods such as the physical habitat simulation system (PHABSIM) clearly unsuitable, South African scientists developed holistic methods (Arthington et al. 1992a). These were applied in Australia when the need for multi-state planning in the Murray–Darling basin, underscored by the Millennium Drought, brought about major changes in water law that called for shifting allocations of water from consumptive uses to the environment (Skinner and Langford 2013).

1.3.2 Science and dispute resolution
Environmental flow assessments almost always occur within the context of disputes over water, and the resolution of these disputes will involve trade-offs and balancing, and often negotiation. For this reason, the main publication on the use of the Instream Flow Incremental Methodology (Bovee et al. 1998) deals extensively with negotiation and dispute resolution. We do not deal with these aspects of the flow-setting process in this review, since we are not experts in them, although we recognize that effective negotiation and dispute resolution are critical aspects of protecting environmental flows. However, it is also important to keep in mind that science and dispute-resolution are separate endeavors that have different rules for settling questions.

Distinctions among human activities often break down in the details, but generally, science settles questions by testing hypotheses or models with data. Procedures for doing this may be generally agreed upon, but they are always subject to criticism, alternatives can always be put forward, and conclusions are always subject to change in light of new evidence. In legal or political disputes, on the other hand, questions can also be settled by the parties agreeing to an answer, and in legal disputes this answer may be final, at least for the parties involved, regardless of new evidence that may emerge. For example, the parties in a dispute over water may agree that the results of a study of part of the stream in question will be taken as representative of the whole. This will not wash in science. Science and dispute-resolution both have major roles in EFA, but it is important to keep them separate.

In the regulatory world, disputes are supposed to be resolved, which requires that decisions be made in reasonable time. This produces a tension between science and dispute-resolution. Adaptive management, discussed in Chapter 6, can be viewed as a way to reduce this tension, but it will not do away with it.

1.3.3 Water is valuable
Because water is valuable, disputes over the allocation between environmental and other uses are often intense. Mark Twain allegedly said that “Whiskey is for drinking; water is for fighting over,” and, even if the quote is not authentic, the comment rings true. If consultants or agency staff on one side of a dispute see their job simply as furthering the interests of their client or employer, then consultants and staff on the other side have little choice but to do the same, resulting in “combat biology.” Something similar results from the tendency of people in a dispute, as social animals, to see their side as in the right, and to accept the opinions of others on their side as correct, with opinions of those on the other side as suspect at best. It is hard to conduct a dispassionate assessment in these circumstances.

1.3.4 Managers or clients often want the impossible
In disputes, properly describing uncertainty can be problematic. Scientists working on EFA normally work for someone else, usually a manager in an agency or consulting firm, or sometimes a specific client, and often in the context of disputes over water. Often, the manager or client will want more definitive results than the state of the science allows. Experience shows that there are scientists who will provide such results, or even the particular results desired, and this presents yet another difficulty for those wanting to do honest work. We wish we had a solution for this problem, but we do not.

A related “real world” problem for EFA is that specialists in the field may build a career around one method or another, and become personally
invested in it. They are then resistant to criticisms of the method that cannot be accommodated by minor changes in it. As Upton Sinclair famously wrote, “It is difficult to get a man to understand something, when his salary depends on his not understanding it.”

Lest this recitation of difficulties seem too gloomy, we reiterate Healey’s (1998) point that people do know quite a lot about fish and riverine ecosystems. We do have a lot of background knowledge and analytical tools with which to think about environmental flow assessment. The rub, however, is that we cannot do a good job of EFA without clear thinking, and clear thinking is as hard to do as it is essential. Therefore, we should do the best we can, be clear about what we did and did not do and why, and try to work in an adaptive framework that will allow changes in management as new information and understanding become available.

1.4 Why EFA is so hard: problems with the literature

There are several literatures on environmental flow assessments or on matters highly relevant to them. It is common to distinguish peer-reviewed journals from agency or consulting reports, but there are also important distinctions among peer-reviewed journals. Roughly, there is a more academically oriented literature, largely in ecological or hydrologic journals, and a more applied fisheries literature, with surprisingly little overlap between them. There are also many relevant papers in journals on geomorphology, engineering, and statistics, and a large literature on habitat selection in wildlife journals. Unfortunately, there are now also “pay to publish” journals that will print almost anything. Even among legitimate journals, these distinctions matter, because the quality of the reviewing tends to vary. Generally, the reviewing for the academically more prestigious journals is more rigorous, but the reviewers for these journals may not be as familiar with the details of a particular topic as reviewers for the relevant specialty journals. The distinction that really matters is whether journal articles or agency reports are based on good logic, methods, and evidence.

Peer review is an important part of scientific quality control, but it is far from perfect and many deeply flawed articles are published. Ioannidis (2005) described this problem for biomedical research in an influential article entitled “Why most published research findings are false,” and the problem has received considerable attention since. For example, the Open Science Collaboration (2015) recently reported that replication of the work reported in 100 psychology articles from leading journals showed that most reported findings were not substantiated. There are various reasons for this unfortunate state of affairs, including conscious or unconscious bias by the investigators, and misuse of statistical methods (the latter is a common one). We are not statisticians, but we often see obvious statistical problems with papers dealing with EFA. The upshot is that even the scientific literature needs to be approached carefully and critically, and those of us who are not experts at statistics should cultivate good relations with people who are. Even apart from statistical issues, we should read the literature with the question “Why should I believe that?” always in mind. Skepticism is particularly justified in reading the EFA literature, as the history of EFA shows.

1.5 Why EFA is so hard: limitations of models and objective methods

1.5.1 Models and environmental flow assessment

Models are essential tools for environmental flow assessment, but are often misused (Chapter 7). The proper use of models is to help people think, even for well-studied physical systems. Consider weather forecasting. The National Weather Service forecasters in our area base their forecasts on the results of three and sometimes four different models, using their knowledge of how well each model handles particular kinds of weather, and the plausibility of each model result. Proper use of models requires a
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good understanding of the model, the data at hand, the system being modeled, and the questions being addressed. A remark by the economist Thomas Piketty seems applicable to ecosystems: “Models can contribute to clarifying logical relationships between particular assumptions and conclusions but only by oversimplifying the real world to an extreme point. Models can play a useful role but only if one does not overestimate the meaning of this kind of abstract operation” (Piketty 2015, p. 70). Inevitably, models embody simplifications of the world, based on the aspects of the world that we (or someone) believe are important for the problem at hand. That is, we model the way that we think the world works, but we should remember that the world has no obligation to work that way. The invaluable thing that models do is to show us the logical consequences of our thinking, or, for estimation models, to show us how well the data support our thinking.

1.5.2 Objective and subjective methods
A few decades ago, it was common for scientists to promote “objective” methods for analyzing problems, generally by applying some numerical model. This conceit has largely been given up, in the face of persuasive arguments that modeling always involves subjective choices. For example, Brenden et al. (2008) used regression trees analysis to develop a classification system for stream segments in Michigan, partly out of concern that a classification based on expert opinion could be hard to defend. However, they deliberately selected a similarity threshold of 0.6, largely because it generated a system “that had good agreement with a previously completed expert-opinion delineation of stream segments” (p. 1622). In modeling for EFAs, there are always subjective choices about what to include in the model and how to do so (Kondolf et al. 2000). Subjectivity will enter into EFAs, whether we want it to or not; the question is whether the subjectivity will be recognized and taken into account.

Just as science should inform EFAs, EFAs should inform science. That is, studies conducted for EFA should be so conducted as to add to the general body of knowledge, and there should be feedback regarding questions and uncertainties that loom large in assessments and may be amenable to traditional scientific inquiry. Thus, the reasoning and assumptions underlying: environmental flow models (EFMs) should be stated explicitly, as should the reasoning underlying environmental flow decisions. In particular, it should be possible to tell what kinds of evidence or new understanding would justify a change in the assessment or the decision.

1.6 Conclusions
For at least two reasons, environmental flow assessment is not just science: the main question it asks may be trans-scientific, and usually the question is asked in the context of dispute-resolution. These qualities are not unique to EFA, but rather apply to ecosystem management generally, which has been called a “wicked problem” accordingly (DeFries and Nagendra (2017). Science can and should inform environmental flow assessment, and EFMs should be consistent with scientific practice. However, the limits to what science can contribute should be recognized. Ecosystems are enormously complicated, and it is not realistic to expect that standard methods can be devised by which EFA can be successfully accomplished without good data, careful thought and informed judgment.