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Valuing Potential Groundwater Protection Benefits

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This paper explores the implications of endogenous risk for the economic value of preventing groundwater contamination. We consider the analytical implications of endogenous risk for five key building blocks frequently used to structure studies of groundwater valuation: the probability and the location of contamination, the exposed population, risk perceptions, and intertemporal issues.

1. INTRODUCTION

Groundwater is a valuable, renewable natural resource that, if contaminated by economic activities, may be rendered a nonrenewable, unusable, and mobile public hazard. Since groundwater contamination is inherently uncertain, efficient resource management requires information on how individuals react to risky events and their preferences for risk reduction. A mechanism to incorporate this information into policy decisions is cost-benefit analysis. Traditional cost-benefit analysis, however, invariably assumes that the individual's ability to influence risk is predetermined or nonexistent. Yet, exogenous risk is a restrictive assumption to apply to the behavior of someone who is confronted with groundwater contamination. Individuals often employ self-protecting activities to reduce the probability or severity of an asset loss. In other words, the individual's risks from groundwater contamination can be endogenous.

For example, an individual can privately test for contamination or leaching. He may then drill a new well or employ private water treatment systems including activated carbon filters, reverse osmosis filters, and installation of systems which vent water to steam. Other private protection mechanisms include use of aerator faucets, nonlead piping, proper disposal of household waste, purchasing bottled water, dumping bleach into a wall, or simply boiling water. These self-protection activities can remove bacteria, organics including fertilizers, solvents, pesticides, herbicides, and inorganics such as lead or cadmium.

This paper explores the implications of endogenous risk for the economic value of preventing groundwater contamination. We consider the analytical implications of endogenous risk for five key building blocks frequently used to structure the groundwater valuation literature: the probability and the location of contamination, the exposed population, risk perceptions, and intertemporal issues. In general, we demonstrate that disregard of endogenous risk can cause the straightforward, piecemeal application of conventional cost-benefit analysis to underestimate the value of groundwater protection, potentially leading to a cumulative loss in groundwater resources.

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Specifically, we argue that the current focus of groundwater protection cost-benefit analysis is misdirected, since it fails to disentangle private and collective contributions to risk reduction. Private risk reduction efforts must be accounted for because differences in human capital among individuals induce differences in their self-protection productivities [*Ehrlich and Becker*, 1972]. Consequently, individuals with identical preference orderings facing a uniform risk will value collective efforts to reduce risk differently according to their private marginal productivities at self-protecting. Therefore in order to establish the true value of preventing groundwater contamination one must consider the value of collective and of private reductions in risk.

In terms of the aforementioned five analytical issues, endogenous risk implies that (1) the notion of the value of a statistical life may be misleading since it does not account for uniquely individual differences in the ability to influence an undesired event, (2) valuation exercises must consider not only specific locations but also lotteries over locations, because conditional uncertainty as to whether a specific site is at risk depends on the protective actions of private individuals, (3) the exposed population should not be multiplied by a uniform probability of contamination to determine value, but rather each individual's unique probability that results from his self-protection behavior must be estimated, and only then can individuals' probability-weighted valuations appropriately be summed, (4) differences in "objective" versus "subjective" risk perceptions may simply be due to the perceived private controllability of the risk, and, finally, (5) applications of uniform discount rates may be inappropriate because marginal rates of time preference will differ because of differences in protection or adaptation opportunities. The basic point is that an individual's valuation is dependent on his productivity at self-protection, and this must be considered prior to any attempt to establish the value of collective efforts to protect an environmental resource such as groundwater.

The paper proceeds as follows. Section 2 categorizes groundwater contamination episodes. Section 3 develops a proposed framework for ex ante analysis based on endogenous risk. The impact of endogenous risk on the five analytical issues is explored in section 4. Finally, section 5 presents the concluding comments.

2. Categorizing Groundwater Contamination Prospects and Episodes

Groundwater contamination episodes can be divided into three categories. Category 1 consists of known, currently existing contamination of a given site. The Love Canal fits this category. Category 2 represents prospective contamination episodes (now unknown but occurring or which may occur in the future) from existing facilities. Every underground storage tank not now known to be leaking is in this category. Category 3 includes those proposed development sites which might introduce groundwater contaminants. This category includes an almost uncountable set of possibilities.

The assessment techniques and requirements for each category differ considerably. In the first the economic issue is one of estimating the benefits and costs of alternative remedial actions in order to determine the appropriate responses to a known episode. The third category involves decisions about the appropriate degree of protection to be taken in designing and locating any future site. For the second category the issues revolve around risk attitudes and perceptions and comparisons of prospective costs and benefits of avoiding damage.

3. A Proposed Framework for Ex Ante Analysis

Given strong policy concerns about groundwater contamination, the economics literature that deals with it is surprisingly small. That literature which does exist deals almost exclusively with existing episodes (category 1) and the attendant human health risks. The studies ignore nonlife threatening health impacts and the anxiety cost of the possible consequences of an approaching plume or one that could change direction due to geological structure. They ignore the potentially large loss in wealth that households may experience if the threat of explosion from petroleum products requires evacuation of house and home.

Most importantly, because they ignore endogenous risks, we believe that the analytical economic frameworks that have thus far been applied to studies of groundwater contamination are deficient in terms of their usefulness to the ex ante design of regulations (category 3) and to the estimation of the ex ante benefits of monitoring existing facilities (category 2). In general, the existing literature such as by *Raucher* [1983] and *Edwards* [1988] assumes that the economic agent is helpless when confronted by groundwater contamination risks. At best, he is only allowed to expend resources to remedy ex post damages; he supposedly possesses no ability whatsoever to anticipate and to modify the potential size of these damages.

Marshall [1976] shows that exogenous risk requires that an insurance (contingent claim) contract exist for every conceivable risk. Because the ex post compensation that the contingent claims supply can then maintain the ex ante utility level no matter what the realized state of nature, there are no differences between ex ante and ex post valuations of risk. However, because the writing and enforcement of contracts is costly, complete contracts rarely if ever exist: if he is averse to risk, the individual must therefore choose ex ante between contractually defining states of nature or making an effort to alter them. These endogenous, ex ante contractual and adjustment opportunities affect the individual's relative valuations of alternative prospective states.

Psychologists, for example, *Perlmuter and Monty* [1979] and *Stallen* [1984], concede that individuals perceive that contractual and adjustment opportunities allow them to exercise substantial control over uncertain events. Though one can always redefine a problem such that the state of nature is independent of human actions, the redefinition will frequently be economically irrelevant. Consider the probability that bacterial groundwater contamination will poison a household's drinking water. The probability of this event can be altered if the householder boils his water. One might redefine the state of the world to be independent of the owner's actions by thinking in terms of the probability of groundwater contamination. The owner may have no control over the probability of contamination. However, this probability is not economically relevant. The owner is interested in the probability of being made ill, and he is able to exercise some control over that event. Risk is endogenous.

Consider a risk-averse individual who must decide how much expenditure s on self-protection to undertake as he confronts the prospect of having some valuable personal asset such as his house or his health h exposed to groundwater contamination r. For a particular liability regime his dilemma arises because his prior self-protection expenditures which reduce the cumulative probability $F(h; s, r)$ and the severity and hence the costs $C(h; s, r)$ of any ex post damages will also cause his ex ante personal consumption to fall. Because of adverse selection, moral hazard, and nonindependence of risks, the individual chooses not to or cannot acquire enough market insurance to avoid the dilemma completely. Given his insurance purchases and given that his utility is intertemporally separable, we suggest that a minimal formulation appropriate to most prospective groundwater contamination problems is

$$\operatorname*{Max}_{s} \left[\int_a^b U(M - C(h; s, r) - s, h)\, dF(h; s, r) \right] \tag{1}$$

where U is a *von Neumann-Morgenstern* [1947] utility index defined over wealth, $W = M - C(\ \ ) - s$ and health h. Expression (1) says that the individual's decision problem is to choose, given a full income M and hazard exposures r, that expenditure on self-protection s which maximizes his expected utility. His probability-weighted utility is a function of his personal consumption and health state, where $U_W > 0$, $U_h > 0$, $U_{WW} < 0$, and $U_{hh} < 0$. Subscripts refer to partial derivatives. At considerable cost in notational complexity, intertemporal and spatial features can, in principle, be introduced into (1) by appropriately defining h, s, and r in terms of time and locational distributions.

The probability weights in (1) are represented by a subjective cumulative distribution function, $F(\ \ )$, defined over the minimum a and the maximum b health outcomes that the individual's genetics and developmental history allow. Presume that the interval $[a, b]$ is independent of self-protection. Let $F_s < 0$ and $F_r > 0$ in the sense of first-degree stochastic dominance. Though the individual acting alone may be unable to influence the extent of pollution, he uses self-protection to reduce his exposure, thus influencing his cumulative distribution $F(\ \ )$ of health states. This probability distribution of health states is dependent upon self-supplied protection s from prospective exposures r. No restrictions need be placed on the signs of F_{ss}, F_{rr}, and F_{sr} in the immediate neighborhood of the expected utility maximizing level of self-protection s^*.

For any health state that the individual might realize, he selects a minimum cost combination of ex post remedial expenditures and health damages. His ex ante efforts to protect himself from exposures influence these ex post costs C such that $C_s < 0$, $C_r > 0$, and $C_{ss} > 0$. The signs of C_{rr} and C_{sr} have no restrictions. The absence of signs for F_{sr} and C_{sr} reflects the possibility that these responses depend upon the environmental concentration (quality) of contamination as well as the extent to which the individual chooses to self-protect [see *Shibata and Winrich*, 1983; *Oates*, 1983].

In order to maximize the expected utility index in (1) one must select a level of self-protection s^* such that the first-order condition

$$EU_W = -E[U_W C_s] + \int_a^b (U_W C_h - U_h) F_s \, dh \qquad (2)$$

is fulfilled. The second-order sufficiency condition is assumed to hold whenever (2) holds. The left-hand side of (2) represents the marginal cost of increased self-protection in terms of the utility of foregone wealth or consumption. The right-hand-side reflects two types of marginal self-protection benefits: the first term is the severity effect, the direct utility effect of enhanced wealth resulting from reduced expected ex post costs; the second term is the probability effect, the indirect utility effect of a stochastically dominating change in the distribution of health outcomes.

The indirect effect is derived by integrating by parts the effect of self-protection upon the $F(\quad)$ distribution:

$$\int_a^b U(\quad)\, dF_s = UF_s|_a^b + \int_a^b (U_w C_h - U_h) F_s \, dh$$

$$= \int_a^b (U_w C_h - U_h) F_s \, dh > 0 \qquad (3)$$

since $F_s(a; \quad) = F_s(b; \quad) = 0$. To get a better understanding of the indirect effect, we can decompose the right-hand-side of (3) further by integrating by parts once more:

$$\int_a^b U(\quad)\, dF_s = (U_w C_h - U_h) \int_a^b F_s \, dh$$

$$-\int_a^b \left[\int_a^h F_s(k \quad)\, dk \right] [U_w C_{hh} - U_{ww} C_h - U_{hh} + 2U_{wh} C_h] \, dh \qquad (4)$$

The first term on the right-hand-side of (4) is the mean effect, and the second term is the spread effect, both defined in terms of second-order stochastic dominance such that

$$\int_a^b F_s \, dh < 0 \qquad \int_a^h F_s(k; \quad)\, dk < 0 \qquad (5)$$

Expressions (3)–(5) imply that self-protection indirectly influences the health state lottery by shifting the mean value of h to the right and by reducing the variance associated with the distribution of health states.

Shogren and Crocker [1991] show among other results that (1) and (2) imply that the marginal value of risk reductions can be increasing and that self-protection expenditures need not be a lower bound to the value of risk reductions. These counterintuitive results can arise whenever there are differences in the marginal productivities of probability-reducing self-protection and of severity-reducing self-protection. Existing risk reduction valuation studies treat the decreasing marginal value of risk reductions and the lower bound nature of defensive expenditures as maintained hypotheses [e.g., *Smith and Desvousges*, 1987; *Bartik*, 1988]. However, the results by *Shogren and Crocker* [1991] suggest that in the presence of incomplete contingent claims markets, traditional evaluations of the economic consequences of groundwater contamination and other forms of environmental risk have neglected plausibly large chunks of economic reality. This neglect combines a disregard of important private adjustment opportunities and a focus upon ex post states. There is some reason to believe that explicit consideration of these factors would have substantial impact upon measures of the economic consequences of groundwater contamination. For example, *Shogren* [1990] and *Shogren and Crocker* [1990] empirically show that if both private and collective opportunities exist to reduce risk, a singular focus upon the collective can readily understate the total value of the risk reduction by a factor of two or more. In succeeding sections we present some specifics of why the analytical basis of the existing literature is excessively narrow when considered in terms of ex ante valuation given endogenous risk.

4. Analytical Issues in Groundwater Contamination Assessment

To illustrate the potential impact of endogenous risk on the cost-benefit analysis of groundwater contamination, we consider five key analytical issues: probability, locational, population, perception, and temporal issues.

Probability Issues

The literature on the economics of potential groundwater contamination assumes that the probability of an undesired state of nature is exogenous to the individual. *Raucher* [1983] is the seminal contribution to the development of an analytical framework for analyzing groundwater contamination episodes and the benefits of protecting groundwater integrity. He defines the expected net benefits at a particular site of a collective protection policy i, $E(NB_i)$ as the expected benefits $E(B_i)$ net of collective protection costs X_i. Thus

$$E(NB_i) = E(B_i) - X_i \qquad (6)$$

Expected benefits are defined as the expected damages $E(D)$ avoided as a result of the policy. The expected damages are defined by

$$E(D) = p_c[p_d C_r + (1 - p_d) C_u] \qquad (7)$$

In (7), p_c is the probability that a contamination episode will occur at the site in the absence of collective policy i, and p_d is the conditional probability that contamination will be detected and human exposure prevented. C_r is the cost of the most economically efficient site-specific remedial response to the contamination episode, and C_u is the cost at the site imposed by continuing to use the contaminated water. Since continued use is one plausible policy response, it follows that $C_r \leq C_u$; that is, economically efficient remedial responses can be no more expensive than passively continuing to use the contaminated water.

Cast in the fashion of (6) and (7), this framework portrays a binary collective policy choice. If policy i is collectively adopted, no contamination or human exposures will occur; if the collective policy is not adopted, human exposures will occur. Though *Raucher* [1986*a*, *b*] and *Edwards* [1988] broaden this binary treatment by allowing collective actions to induce continuous probability changes, they still have the probability of detection and the probability of exposure appear as exogenous to the individual to whom the benefits of contamination prevention will accrue.

Main [1986] breaks the cost of detection down into the cost of cleanup with detection prior to exposure C_N^1 and the cost of cleanup subsequent to exposure C_r^2. The cost of cleanup and human exposure is thus $(C_r^2 + C_u)$. While this allows *Main* [1986] to capture the cleanup timing problem, he also treats the probabilities of C_r^1, C_r^2, and $(C_r^2 + C_u)$ as exogenous to the individual.

Raucher [1983, 1986*a*, *b*] and *Main* [1986] presume that benefit-cost analysis influences collective efforts to alter detection, contamination, and exposure probabilities. Because they treat these probabilities as exogenous to the individual, they are able to base their benefit-cost analyses on the value of a statistical life, a measure of the cost of a single death weighted by a uniform probability of suffering it. However, even though each member of a set of individuals may be uniformly exposed to an environmental hazard, one cannot easily assume that each person faces the same probability of suffering from the undesired state. Individuals may have identical preferences. They may nevertheless have very different probabilities of realizing the undesired state because they differ in their abilities to self-protect from exposures to contaminated groundwater. Thus the uniform value of statistical life or limb approach to benefits determination that Raucher and Main suggest ignores the differences in individual risks induced by self-protection activities. Since these self-protection activities differ with individuals' capital stocks and access to contingent claims markets, complete valuation requires consideration of the individual's willingness-to-pay for collective and for private risk reductions. Otherwise, the exclusive focus on collective action that Raucher and Main profess will undervalue the protection of groundwater resources, leading to economically excessive levels of contamination.

Locational Issues

The *Raucher* [1983, 1986*a*, *b*] specification of C_r as the site-specific, least-cost remedial measure can generate a bias toward sacrificing regional groundwater integrity. This piecemeal approach fails to recognize that for technical or economic reasons the least-cost remedial measure may be the collective or the private substitution of another regional groundwater source. The source might be moved to the individual; alternatively, the individual might move to it. The cost of resorting to this substitute will clearly depend upon its state of contamination. This mode of adaptation implies that neither the benefits of preventing contamination at a given regional site nor the costs of remedial actions at this site can be evaluated independently of the distribution of groundwater contamination throughout the entire region. Consequently, even site-specific valuation exercises must be constructed in terms of contamination lotteries defined over a set of locations rather than being limited to the specific site. In addition, the exercises must consider the individual's ability to influence these lotteries and the timing of their outcomes. For example, someone who dumps bleach into his well is not only reducing the contamination of his own groundwater supply, he is also enhancing the suitability of this supply as a potential substitute source of water for another contaminated site. Failure to account for these substitution possibilities will understate the value of groundwater protection.

Population Issues

Raucher [1983] does not refine the C_u measure. In his applications he takes C_u to be either realized crop yield loss from irrigating with contaminated water or realized health damage from drinking the contaminated water.

Schechter [1985*a*, *b*] formalizes the health impact by assuming

$$C_u = (M_r)(L)\text{Pop} \tag{8}$$

where M_r is the incremental health risk, L is the monetary value of life, and Pop is the size of the exposed population. The monetary value of life L is taken to be the representative individual's maximum willingness-to-pay for a small increment in safety and is given by *Sharefkin et al.* [1984] as

$$L = \frac{U(W)}{(1 - M_r)U'(W)} \tag{9}$$

where W is the individual's wealth or discounted lifetime income, and $U(W)$ is the individual's utility function. In this formulation, L is the value of a "statistical life" rather than one which is individual-specific. Expression (9) also presumes that health is valued only insofar as it contributes to income, a presumption that individuals not in organized labor markets would question.

The approach in (8) and (9) is also problematic because it treats the health risks imposed upon individuals as involuntary. Again, since individuals self-protect according to differences in productivity, one cannot aggregate over all individuals while ignoring their private abilities to self-protect. The proper method to aggregate values is to account first for individual probabilities given private protection and only then to aggregate values across the exposed population.

Perception Issues

As *Weinstein and Quinn* [1983] argue, a central source of difficulty in measuring the economic consequences of risky events is the divergence between "objective" or "scientific" measures of risk and the individual's perceptions of such risk. Objective damages are calculated as an objective probability of death (usually drawn from the best available natural science evidence) times a dollar value for safety (usually drawn from labor market studies). In contrast to such "damages", perceived damages for an individual are equal to his perceived (i.e., subjective) probability of death from the environmental risk at issue, times a perceived value of safety. The possible difference between these two measures of damages raises a fundamental policy problem, although *Raucher* [1986*a*, *b*] dismisses the subjective assessments as not relevant to the policy decision. Raucher's position is debatable for endogenous risk. The divergence between "objective" and "subjective" risk is often due to the individual's perception of controllability [*Stallen*, 1984]. This implies that self-protection opportunities influence subjective risk. In turn, this subjective risk determines the individual's chosen self-protection behaviors. It is these behaviors that determine his value of safety. Moreover, this further implies that the individual's objective probabilities of suffering harm are not independent of his subjective probabilities.

Intertemporal Issues

It is not just the current population but also future populations which count in (8). *Schechter* [1985*a*, *b*] acknowledges intergenerational equity issues in groundwater contamination. Nevertheless, there are subtle intertemporal issues short of mutations appearing in future generations that need to be considered.

Since groundwater can move slowly, the timing of a contamination episode may be separated by years or decades from the original spill if not detected early (recall the framework of *Main* [1986]). Housing developments may unknowingly be situated in the path of a contaminant plume that started from a leak in the past. A cost-benefit calculation that either ignored population projections or was based on faulty projections would underestimate the likely damages because the housing development was not foreseen and hence not included.

In addition, the outcomes of programs to alter environmental resources are not immediately realized and then abandoned nor are the alterations necessarily permanent. Unless the individual is myopic, it follows that the instantaneous expression in (1) must be modified to account for the temporal dimensions of his decision problem. In principle, this modification is not difficult: one simply redefines (1) as in the book by *Hirshleifer* [1970] to include time-state-dependent claims rather than just state-dependent claims. Even in the absence of complete contingent claims markets which allow the individual to arbitrage away any differences between his impatience and the after-tax market rate of interest, one might, as in the paper by *Graham* [1981], adjust the riskless rate to reflect this absence. In either case, custom first demands separate estimation of the relevant surplus (value) measure in each period and then application of the appropriate discounting formulae to the resulting stream of instantaneous consumer surpluses. The conclusion is an estimate of the present value of alternative time-state-dependent claims.

However, while using logic similar to our model in (1)–(5), *Blackorby et al.* [1984] show that the custom is incorrect even when utility is intertemporally separable. By focusing solely on within-period effects, the customary procedure fails to account fully for the individual's opportunities to adapt to the effects of a risk-induced compensating income change in a particular period. In particular, it does not allow him to intertemporally redistribute his consumption and investment activities so as to equalize his marginal utility of income across periods. The individual's implied marginal rate of time preference (his discount rate) will obviously depend upon this intertemporal redistribution. Le Chatelier effects imply that the customary procedure will underestimate the present value of a time stream of environmental improvements and overestimate the present value of undesirable changes.

Given that contingent claims markets are incomplete, that access to these markets differs among individuals, and that the individual's marginal rate of time preference is endogenous, the oft-debated question of the appropriate uniform discount rate across individuals becomes less significant. If consumer sovereignty commands respect, then discounting must be viewed as a personal decision based on the individual's marginal productivity at self-protecting by intertemporal redistributions of his consumption and investment activities. Given the endogenous risk phenomenon that this intertemporal redistribution implies, it also follows that individuals' valuations of protected groundwater should be aggregated only after accounting for each individual's private marginal rate of time preference.

As noted by *Rosen* [1988], considerable research has examined intertemporal risk affecting life expectancy where risks are implicitly valued at various points in the life cycle. Rosen examines risk valuation over the life cycle where self-protection is assumed not to exist. This exogenous risk perspective is consistent with the previous literature but not with our argument of endogenous risk. *Keen* [1990] provides some empirical detail on the valuation consequences of disregarding intertemporal substitution possibilities.

5. CONCLUSIONS

The small number of existing studies on the value of inhibiting groundwater contamination may legitimately be viewed as precise. Precision does not guarantee that their value estimates are either accurate or complete. Current assessments typically ignore many dimensions of the economic consequences of groundwater contamination. In particular, the existing literature fails to disentangle the collective and the private provision of protection, insurance, and remediation. It thus produces unnecessarily restrictive policy-relevant information about the relative importance of collective and private influences upon valuation. Inadequate model formulations may lead to inaccurate estimates of economic consequences. Further, the current assessments fail to include the full set of physical consequences associated with groundwater contamination. This implies an undervaluation of contamination effects. Future research directed at refining and extending some of the model issues and formulations discussed here thus seems worthwhile.

In conclusion, endogenous risk raises the issue of ex ante/ex post choice in the welfare economics of uncertainty. Standard welfare theory aggregates individual preferences to obtain a social welfare function. Under uncertainty, the social welfare function can be expressed in terms of the ex ante or the ex post state of the world. An ex ante choice implies that the welfare function is derived by maximizing individual expected utility (using individual perception of risk) and summing across individuals. The ex post choice derives a social welfare function by summing individual preferences under certainty, weighting them by the risk perceptions of experts, and then summing to obtain maximum aggregate expected welfare. *Hammond* [1981] demonstrates that the ex ante and the ex post approaches will be equivalent if and only if (1) all individuals have the regulator's perception of risk and (2) the social welfare function is a weighted sum of individual utilities under certainty.

A social welfare function should respect individual preferences. However, *Sandmo* [1983] points out that although preferences are usually assumed synonymous with "tastes," the regulator might not respect individual (mis)perceptions of risk. The regulator must decide whether to use individual perceptions (ex ante) or to use his own perception (ex post) derived from expert opinion.

Suppose experts conclude that a risk from a given environmental state is unacceptable but the public nevertheless chooses to use this environment. Does the regulator ban the environment or allow individuals to use their own discretion? The dilemma is to balance the tradeoff between preserving individual freedom of choice and maintaining public safety. The regulator may be tempted to regulate the risk in his view of the best interest of society. Such paternalistic action, however, conflicts with our society's commitment to consumer sovereignty, that is, the individual is best able to judge what is in his or her own self-interest. Even if there is no such conflict, any regulator inattention to individuals' abilities to employ discretion (endogenous risk) guarantees that his predictions of the economic consequences of his policies will differ from actual consequences.

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