CONTINGENCIES, TRANSIENT EVENTS AND RELIABILITY IN MANAGING WATER QUALITY

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Abstract. If the implementation of current regulations for environmental protection were to be entirely successful, and if urban wastewater were to be treated entirely at source, what would be the nature of water pollution control in the long run? Would an alternative style of regulation be needed and thus a different strategy of monitoring the environment? How might we acquire the knowledge base required to guide and inform the associated decision-making process? These are the sorts of questions that provide the motivation for this paper. In particular, it addresses problems of the reliability of contaminant removal and recovery from wastewater, the handling of contingencies, and the attenuation of transient pollution events associated with land-surface runoff.

INTRODUCTION

For the time being it is safe to assume that the regulations governing protection of the environment will become more stringent and be applied more comprehensively. We should expect that on average the quality of water bodies will increase and thus be restored to a level that society will swiftly come to accept as indispensable to an appropriate "quality of life". We can equally so expect that the physical infrastructure controlling the return of urban sewage to the environment, i.e., sewers and wastewater treatment plants, will reduce to a very low level the normal rate of discharge of the associated residual contaminants to receiving waters. From these assumptions, three conclusions of strategic importance for the future of water quality management can be drawn. First, any transient degradation of quality in a body of water of generally good quality will be increasingly apparent and of concern to the public. Indeed, this is precisely what has occurred following rehabilitation of the Rhine in Europe (Malle, 1994). Second, the probability of faults and failures in the increasingly complete and high-performance wastewater infrastructures of cities will grow; and the accompanying potential for damage from the resulting transient pollution events is also likely to grow. Third, the causes of pollution will increasingly be perceived as a function of factors not associated with the normal, day-to-day domestic and commercial activities of an urban population. That is to say, they may become primarily a function of transient land-surface runoff from precipitation-induced events.

There is accordingly a need for intensive monitoring of the unsteady-state behavior of wastewater treatment and receiving water systems when subjected to transient disturbances. From such field observations models may be constructed and used for exploring and developing strategies of management directed at improving the reliability of operation of these systems. It is the purpose of the paper to present a strategic perspective on the manner in which the rather different problems of the future might prompt the opening up of novel avenues of research. We need first, however, some conceptual apparatus with which to identify the origins and form of these emerging problems. It must also be acknowledged, from the outset, that our discussion will be biased towards catchments in which urban activities predominate.

TOWARDS A FUTURE PATTERN FOR MANAGING WATER QUALITY

The Conceptual Framework

It is in fact not at all easy to define what should constitute the *system* -- that piece of the real world in which one has a special interest -- when in reality things move in cycles (notably here the hydrological cycle and global material flows). But let us focus our attention on precipitation and other deposits on the land surface as our collection of primal *inputs* and on streamflow and its burden of constituents as the *outputs* of concern to us. The system, therefore, comprises just the terrestrial component of the hydrological cycle, within which the use of land may be classified as urban, agricultural, or forested.

In order to explore man's impact on the system so defined, including our attempts at controlling this impact over time, we need a conceptual framework for quantifying both the collective pattern of input perturbations and the manner in which the outputs of the system may respond to these stimuli. In the present case the spectrum of frequencies of input disturbances of the system is a natural, but not the only, choice. For our system will be subject to oscillatory changes in the long term over millennia, centuries and decades; we might call these low-frequency disturbances, typically associated with changes in climate. At the opposite end of the spectrum it will also be subject to relatively high-frequency perturbations at weekly, diurnal and hourly scales, in association with society's habits and singular precipitation events. The output response of the system to this spectrum of input perturbations can be gauged in two ways: more familiarly (i), according to whether the magnitude of the incoming oscillation is amplified or attenuated in the output response; and (ii), according to whether the peak (or trough) in the output response is delayed or brought forward in time relative to the peak (or trough) in the input disturbance.

Such a form of *frequency response* analysis is helpful from many perspectives, but not sufficient on its own. It must be complemented by an appreciation of the changes experienced by the system more directly in the *time domain*. In particular, we shall need to conceive of "equilibrium" conditions (assuming they might approximately prevail for some span of time) and of *transient* perturbations about this equilibrium. Most familiar, in this respect, will be the notions of (a) an impulse-like response in the system, starting from and returning to the same equilibrium condition, and (b) a step-like response, in which there is a movement from one to another equilibrium condition.

What we seek to establish through such an analysis in the *dynamic* dimension of the system's behavior, albeit qualitatively, is a contemporary impression of the requirements for monitoring, modelling and managing the water quality of river basins. If the nature of the problems is changing, we wish to know in what way and, hence, whether our current approaches to their solution are appropriate.

Urban Activities

Let us examine then what has been the impact of urban development, when viewed as a transient perturbation of the pre-existing "pristine" hydrology of a river basin in an instant of geological time. At the onset of the perturbation, there was migration of population into the city; then the installation of a centrally organized water supply to the city; the installation of sewerage for the conveyance of wastes out of the confined spaces of the city; followed by wastewater treatment; and then successively more effective wastewater treatment. Surface waters, which prior to this perturbation had been subject to seasonal cycles of disturbances and the disturbances of precipitation events, became subjected to an entirely novel band of perturbation -- of a predominantly diurnal frequency and of a predominantly qualitative character. Having successfully installed the infrastructure of sewerage and centralized wastewater treatment, we are now -- in the late 20th Century and in river basins at a mature stage of social and economic development -- witnessing a return in the behavior of the perturbed system to some pre-city equilibrium. The spectrum of input perturbations is again as before, dominated principally by seasonal fluctuations and the high-frequency disturbances of precipitation events.

In total, the foregoing charts merely the transient impact of the city on the surface-water sector of hydrology. It has isolated the system's response to perturbations associated with society's diurnal and weekly habits as the principal change in the spectrum of fluctuations in this response. Yet the creation of impervious surfaces and the installation of sewerage has both the effect of accentuating the amplitude of surface-water responses to the high-frequency rainfall events and of lowering the overall rate of water infiltration to the sub-surface groundwater sector of the hydrological system. In a sense, an element of damping and peak-attenuation has been lost from the rainfall-streamflow system. In these respects the impacts of the city -- in the long run -- have hitherto been of a less impulsive-like transient and more of a shift from one prevailing equilibrium state to another.

It is both obvious and a truism that the installation of a wastewater infrastructure, no matter how clean and sustainable, cannot entirely restore the city's environment to a pre-city status. The spectrum of perturbations to which that environment is subject will have been forever changed and, most notably, in respect of a new category of events that we can broadly call *infrastructure failures*. It hardly needs stating that these will be all the more significant because of the restorative successes that have followed from installing the infrastructure in the first place.

To summarize, the following categories of changes to the spectrum of perturbations of the system wrought by the impact of the city can be identified: (i) amplification of fluctuations in the mid-frequency (diurnal and weekly) band of the spectrum as a function of population concentration; (ii) the introduction of a band of higher-frequency perturbations associated with infrastructure failures; (iii) alteration of the relative distribution of low- (infiltration) and high-frequency (runoff) fluctuations due to the substitution of vegetation by impervious cover and the implementation of artificial conduits (sewerage); and (iv) the introduction of high-frequency polluting events as a result of contaminants entrained into either or both of the atmospheric and land-surface segments of the hydrological cycle (gaseous sulphur and nitrogen species and particulate road surface deposits, for example).

We now review briefly comparable changes in systems dominated by non-urban activities.

Agricultural and Forestry Activities

The concentration of human population in cities that has promoted a mid-frequency band of diurnal and weekly disturbances of the hydrological cycle is not relevant to the behavior of agricultural and forested catchments. Similarly, infrastructure failures are not as readily apparent where the predominant land-use is other than urban. Both of these statements, however, discount any growing significance of intensive livestock production and the installation of an associated infrastructure for the collection and treatment of residuals arising therefrom.

The impact of vegetation change occasioned by the creation of a city is, in contrast, just as relevant to these latter land-uses (Hatfield, 1993; Binkley and Brown, 1993); there will tend similarly to be a loss of capacity for attenuation and damping of the overall, higher-frequency runoff-streamflow responses. In the case of forested catchments, where shading effects are important, the removal of vegetation cover has a compounding impact on the loss of damping capacity at the higher (diurnal) frequencies of system behavior. The response of stream temperature to solar radiation patterns may thereby be significantly amplified, with its attendant problems for fish survival (Binkley and Brown, 1993).

The fourth category of changes in the spectrum of perturbations -- of novel or excessive amounts of contaminants entrained into precipitation event responses -- has long been of relevance to agricultural and forested catchments (although not widely addressed in the hydrological sciences until relatively recently).

THE GENERIC PROBLEM

In reality, we know that the system is perturbed by, and responds to, an *entire* spectrum of fluctuations, over millennia, centuries, decades, years, seasons, weeks, days, and hours. We know too that perturbations and responses at one frequency are not independent of changes taking place at another frequency. For example, the removal (and replacement) of vegetation cover will usually enhance (suppress) the movement of particulate soil matter from the land into the surface water environment over a period of years and decades. For as long as any contaminant material associated with this particulate matter can accumulate within the surface water system in a labile form (as erodible sediment) it will influence the high-frequency precipitation-event response until the longer-term transient has receded to its prior equilibrium condition. Similarly, the longer-term accumulation of land-applied nutrient residues in impounded river sections and lakes will foster conditions ripe for the high-frequency oscillations of algal bloom/die-back events. An especially rich discussion of cross-spectrum relationships in phytoplankton ecology can be found in Harris (1980).

This inter-connectedness notwithstanding, our attention must now be focussed (albeit briefly) on the nature of the *generic* problem to which the paper is addressed. Quintessentially, it is this: relative to some lower-frequency oscillation, each higher-frequency oscillation can be seen as a *transient perturbation about an equilibrium*. Hitherto, strategies for managing water quality have dealt predominantly with the goal of taking action, i.e., defining regulations and constructing infrastructures, to achieve an improved equilibrium at the scale of seasons and years (Beck, 1985; Beck et al., 1991). There is no argument but that this *has* been the correct approach. Yet relative to the equilibrium of the annual cycle, high-frequency, transient pollution events have largely been ignored, or were not perceivable as a problem until very recently. For one thing there has not been the relevant monitoring capacity. But more significantly, the perception of a transient perturbation of given magnitude will differ greatly as a function of whether it is set in the context of a low or a high equilibrium value of ambient water quality.

A broader perspective is now needed. It is needed, inter alia, for the most curious of reasons that perhaps could not have been anticipated. Malle (1994), for instance, has noted that transient pollution events in the rehabilitated Rhine are all the more significant because of a decline in resident bacterial populations, which had previously been supported by ample supplies of wastewater. Nitrobenzene will now be apparent as a result of an accidental spill, when previously it would have been more swiftly degraded before propagating very far. Rehabilitation may make the system appear to be more vulnerable to disturbance than we might previously have imagined. Do we, then, have the appropriate monitoring strategies for improving the understanding of higher-frequency transient behavior? Are there models available for encoding this knowledge base? By what instruments of management might we attenuate the deleterious impacts of these transient perturbations? Indeed, more fundamentally, what might be considered a desirable and what an undesirable perturbation?

ADDRESSING THE PROBLEM

The Undesirability of Transient Perturbations

Certain forms of transient perturbation can be agreed, without great debate, to be undesirable, such as our categories of infrastructure failure and precipitation-associated events bearing abnormal substances or abnormal amounts of substances relative to some location (or sector of the environment).

The undesirability of other forms of perturbation is far less clear cut; and clarification thereof is most unlikely to be swift in coming. For this has to do with ethical aspects of how we believe the environment should be managed and with profoundly difficult questions of how ecosystems have evolved in response to perturbations (Reice et al., 1990; Grossman et al., 1990; Whitfield, 1991). Gore et al. (1990), for example, define one of two alternatives for a perturbation (disturbance) of an ecosystem as being "... an unusual (or unpredictable) deviation from normal conditions". Thus in piedmont streams of the southeastern USA frequent floods that "... keep the macroinvertebrate community in perpetual disequilibrium ..." can be argued to be the norm (Reice et al, 1990). This being the case, we might only be able to advocate safely that a goal of management should be to move towards restoration of the *entire* spectrum of perturbations to which a given system might once have been subject. Restoration of the natural balance of low/high frequency perturbations associated with a naturally vegetated system (following urbanization) might then be accommodated as desirable. But in turn we would have to define what is meant by "natural" or "naturally", and so on. For the present paper little more can be done other than to acknowledge that these broader issues will have a bearing on how transient events are managed, but in an as yet undefined manner.

We have asserted, without deep philosophical justification, that infrastructure failure represents a novel and undesirable category of transient perturbation about an equilibrium. Its possible forms need now to be given a more detailed definition.

Reliability and Infrastructure Failure

The purposes of a city's wastewater infrastructure are: (a) to avoid flooding through the manipulation of flows of surface runoff; (b) to transfer "waste" materials from one location to another using a carrier medium (water); (c) to recover the carrier medium as a resource (for reuse and environmental preservation); and (d) to recover and utilize products associated with the solid "wastes" separated from the recovered carrier medium. In the cycle of things it is hard to determine what is truly a "waste" material (hence the precaution of wrapping this word in quotation marks).

The origins of potential threats to the reliability of the wastewater infrastructure in providing these services must now be established. We shall distinguish three such ad hoc classes of threat: external, physical stimuli; equipment failure; and human error, including an (inevitably) incomplete knowledge base.

We know, first, that precipitation-associated events, which may be deemed abnormal because of unexpected variations in their burden of particulate and dissolved materials, constitute one class of disturbance affecting achievement of all the above purposes except that of (d) -- the solids recovery sub-system has a high capacity for attenuating high-frequency disturbances. The biochemical transformation of materials in transit through the infrastructure is dependent upon the residence time of this flux, which is obviously a function of flow velocity. Thus, for example, during storm events the time available for the hydrolysis of organic materials to volatile fatty acids prior to arrival at the treatment plant may be insufficient to sustain biological phosphorus removal. In this, and in other ways (notably the washout of nitrifying biomass; Lessard and Beck, 1990), high-frequency perturbations may induce lower-frequency disturbances within the infrastructure, whose adverse consequences are subsequently transmitted to the receiving environment. There is further a sub-class of these problems arising from the accidental spillage of undesirable substances into any part of the infrastructure (the sewer network, the treatment plant) and, to be complete, the receiving water body (Malle, 1994).

Second, abnormal disturbances will arise within the infrastructure itself, not as a result of any external stimulus, but as a consequence of the failure of mechanical and electrical equipment, i.e., within the monitoring and actuator sub-system of the infrastructure.

Third, human error may in addition be associated with the procedures for controlling the operation of the infrastructure. It is perhaps less self-evident in the form of unexpected, abnormal behavior in the unit process technologies themselves. These technologies seek to exploit a variety of physical, chemical and biological principles. There are uncertainties surrounding the practical realization of all of these principles, but especially those underpinning the engineering of biochemical mechanisms of treatment, many of which may lead to failures, in particular, in the performance of the secondary clarification unit (Chen, 1993; Chen and Beck, 1993). One such class of failure is due to an inability to separate a bulking sludge -- arising from an imbalanced growth of bacterial species -- from the recovered carrier medium.

Monitoring

It has been suggested that past approaches to monitoring have been bound not merely by technological limitations but also by the nature of our administrative culture (Whitfield, 1991). Progress in understanding the behavior of wastewater treatment, for example, was undoubtedly hampered in the mid-1980s by access to routine (administrative) operating records alone (Beck, 1994). But more broadly, the common experience was, above all, for the successful development of models to have been compromised by too slow a sampling frequency of field observation (as apparent, in retrospect, in the early studies of surface water acidification; Beck et al., 1987). In short, but a narrow bandwidth of behavior -- of the order of days, weeks, and months -- has been monitored for the purposes of river basin management (Whitfield, 1991).

We may therefore expect that increasing access to the new technology of the past two decades will rectify this imbalance (Whitfield and Wade, 1992). There might, however, be some subtle complications that follow in the wake of this simple rectification. One of these is the matter of quality assurance in the automated capture of data (Whitfield and Wade, 1993; Nyberg et al., 1993; Watts and Garber, 1993); and this in turn raises issues of reliability. We might suppose that decision-making will experience an increasing exposure to a knowledge of imminent high-frequency disturbances. Awareness of high-frequency disturbances implies correspondingly high-frequency actions directed at disturbance attenuation, so that we may see a move to a higher-level of risk assessment. Dramatic action in the face of a high-amplitude, high-frequency disturbance brings with it the burden of rapid cost and damage assessment, not least in respect of whether to issue a warning of impending danger. The problem of reliable discrimination between a true and a false alarm is, of course, akin to the classical problem of issuing flood warnings. It is already becoming an integral feature of biological "early warning" systems designed to detect the presence of abnormal levels of contaminating substances (Borcherding and Volpers, 1994; Puzicha, 1994).

Modelling

The need to restore a more desired equilibrium condition in the environment has been largely served by the use of assumptions and models characterizing a steady-state condition, both in respect of the receiving water body (Barnwell et al, 1987) and in the design of the wastewater infrastructure (Harremoës et al., 1993). The convenient simplicity of an assumed steady state has likewise underscored the development of ecology: "[t]hroughout most of this century, the dominant paradigm of community dynamics was that systems were at equilibrium" (Reice et al., 1990). Or, put rather more completely (Harris, 1980):

> *[A] quasi steady-state view of phytoplankton ecology has led to a paradigm in which the role of variations in the environment at periods less than 1d or longer than a year or so has been emphasized less than the mid-range of variations. This, coupled with a sampling routine which resolves only such scales, immediately biases the whole emphasis of phytoplankton ecology.*

In reality, a steady state is a fiction. In the vast majority of engineered systems, however, it is a state much coveted. Yet it is not a state from which we can gain much understanding of the functioning of a system; and such understanding may be pivotal in ensuring that operation at an equilibrium point, if desired, is both achievable and achieved.

In principle, it is not difficult to construct models that are suitable for characterizing transient perturbations about an equilibrium (Lessard and Beck, 1990; Harremoës et al., 1993; House et al., 1993; Bildstein and Vançon, 1994; Beck and Reda, 1994). One needs only *not* to take the step of invoking the assumption of a steady state. Indeed, in the broad setting of this paper, with its links to hydrology, the mere statement of this fact will seem entirely redundant to many.

There is, of course, a significant difference between constructing a model in principle and evaluating it in practice. In the present discussion this difference is not as straightforward as the additional difficulty of having to conduct monitoring exercises geared to an unpredictable transient as opposed to a more predictable equilibrium. For as with the expected progress in monitoring, there are subtle complications. These are essentially those of the need to understand the interconnectedness of perturbations across a spectrum of scales: as so eloquently illuminated in Harris's (1980) discussion of phytoplankton ecology; and as vital as in the design of field work for the characterization of upland surface water acidification (Wheater et al., 1993) or for the evaluation of models of water quality in the Chattahoochee (Department of Natural Resources, 1994). Equally of significance, and in contradistinction to the more classical aspects of an intervention analysis (for example, Booman et al, 1987), the detection of a transient perturbation may be apparent principally from a shift in the amplitude of high-frequency fluctuations about an unperturbed mean equilibrium (Whitfield and Wade, 1992). Alternatively, at the other end of the spectrum, low-frequency perturbations as a consequence of changes in vegetation cover may now be better identified precisely because a model can be used to remove the clutter of high-frequency rainfall-runoff responses and noise from the catchment observations (and because we now have longer catchment records with a consistently high sampling frequency; Jakeman et al, 1994).

ISSUES OF MANAGEMENT

Criteria of "Goodness"

The archetypal form of transient perturbation about an equilibrium condition is that which induces what would intuitively be described as an impulse (or pulse) response in the behavior of the system. It has three easily quantifiable attributes, all of which may be defined at a point location: (i) the extreme of the response, e.g., the maximum concentration of ammonium-N or the minimum concentration of dissolved oxygen; (ii) the duration of the response above (or below) some pre-specified "acceptable" concentration of a substance; and (iii) the mass flux (or load) of material passing the given location, such as a reach boundary in a river. Computation of these attributes has already been explored as a means of discriminating among appropriate design and control strategies for attenuating the impacts of storm sewage events on the performance of a wastewater treatment plant (Lessard and Beck, 1990). In this straightforward context, "goodness" of control would be equivalent to the joint minimization of peak response, event duration, and integral mass flux.

Such matters are rarely this straightforward, however. Our archetypal event has been defined at a point location, for a single chemical species, relative to a span of time containing but that single event. Success in management will almost certainly have to be judged in a wider context, wherein the characterization of events will need to be extended to embrace broader facets of each of the three dimensions thus introduced, respectively: space; the spectrum of physical, chemical, and biological system species; and, not surprisingly, the spectrum of temporal fluctuations.

Thus, for example, van Baardwijk (1994) talks of the severity of an accidental release of contaminating material as being gauged according to the maximum *volume* of water attaining a given concentration of the contaminant (presumably at any instant during the span of the defined event). Integration over space can thereby be achieved. In the face of myriad physical and chemical species of contaminant, it has long been appreciated that the integrative response of an organism -- or at most a small number of organisms representative of the *ecological system* of the affected water body -- is an effective means of detecting a perturbation and gauging the success or failure of management (Cole et al., 1994). Organisms, however, are adaptable. Their capacity for acclimation, to seek refuge, to exhibit post-exposure recovery, or to undergo delayed mortality -- all characteristics that distribute the nature of their response to perturbations over a range of time scales -- will undermine the ability to judge the quality of management on a single-event, singular-frequency basis. Attaching the return period of an event to the attributes of duration and peak response (as in flood control) achieves a degree of integration over a wider span of the *frequency spectrum* of transient perturbations (House et al., 1993).

Prevention, Attenuation and Recovery

The actions of management can be classified according to whether they are to be applied (a) before, (b) during, or (c) after the event. Historically, the city's wastewater infrastructure was installed after the event and, significantly, in response to an observed detrimental effect. Yet the instruments of management may be applied not solely on the basis of a type of event that is known to *have* occurred but also on the basis of what is believed *might* occur, and before it does. Nowhere is the latter more apparent than for the class of transient perturbations defined earlier as infrastructure failures. In determining an associated set of preventative measures, thought must be given in an organized way to the range and combinations of modes of failure (van Baardwijk, 1994). Indeed, for obvious reasons, this is a most earnest business in the nuclear industry (Davis et al., 1990). If the probabilities of failure of the infrastructure and the resulting damage to the environment can be quantified, the possibility of a risk-based approach to management is thereby enabled (Chen et al, 1993) and the costs and benefits of successful action might thus be balanced against the costs of failure.

The scope for control in real-time -- during and after the event -- can easily be imagined. Indeed, the notion of an integrated approach to the coordinated control of material fluxes across the entire urban drainage complex, including the receiving water body (Beck and Reda, 1994), is an idea whose time seems finally to have come (Harremoës et al, 1993; Somlyody, 1994). Such action may seek not only to suppress the extent of the damage of the event, but also to accelerate recovery therefrom, as in re-seeding with viable biomass an activated sludge unit that has lost its nitrifying capacity (Szulc, 1991).

Cross-spectrum Effects

There are times when isolating the individual event from the clutter of the background is of great advantage. There are times when it can be just as much a disadvantage. A high-frequency disturbance may provoke a transient response in the longer term and high-frequency responses may vary as a function of lower-frequency fluctuations. For example, we have found from simulation results that very high-frequency control action (manipulation of biomass recycle on an hourly basis) can have an important influence over suppressing a bulking sludge in the longer term, where its occurrence may be promoted through low-frequency, seasonal perturbations in load variations (Chen and Beck, 1993). Or alternatively, real-time control of flows through an urban sewer network will compensate for the amplification of high-frequency disturbances transmitted to the receiving environment by the installation of the network in the first place. However, substantial success in the capture of storm sewage flows and their routing to treatment would not necessarily be without penalty. The lack of reliability in secondary clarification (Harremoës et al., 1993) is likely to be exacerbated at elevated equilibrium hydraulic loadings with much reduced scope to withstand a high-amplitude, high-frequency perturbation should it occur.

There are, then, cross-spectrum effects, whose analysis and resolution may not be best served by the convenience of separating the parts from within the whole (as is especially apparent from Harris's analysis of phytoplankton ecology; Harris, 1980). The goal of managing transient perturbations about an equilibrium might have to be set within the strategic context of restoring the *entire spectrum* of the system's behavior to some quasi-pristine template. In other words, if the system was subject to modest low-frequency, little mid-frequency and much high-frequency perturbation in this quasi-pristine state, the objective of management would be to restore this particular spectrum of disturbances. There is, for example, a school of thought -- with rapidly growing support -- that seeks to rectify the distorted spectrum of perturbations associated with the creation of impervious surfaces and "wide-area" sewerage in the urbanization of land. At the pragmatic level, it promotes relocating the point of application of the technology and practices of storm-runoff control from a centralized, "end-of-pipe" location (close to the recipient target of pollution) to a multitude of spatially distributed local facilities for "source control" (Ellis, 1989; Roesner et al., 1989; Urbonas, 1994; Somlyody, 1994). This affords greater scope for matching a particular technology with a particular type of runoff (road, parkland, residential) and an enhanced capacity to capture and treat the first-flush of pollutants carried in the runoff (Livingston, 1989). If further these source controls were to make extensive use of infiltration to the sub-surface water sector, they would have the longer-term restorative effect of returning the system and, importantly, its spectrum of perturbations, to a pre-city condition (Geldof et al., 1994).

At a more philosophical level this movement towards source controls is consistent with the contemporary maxims of achieving sustainable development through, in part, the installation of clean technology (Geldof et al., 1994). In both Geldof et al. (1994) and Beck et al. (1994) appeals are made to the analogy of an organism's metabolism in order to establish what principles should be used to determine the goal of technological applications in the urban drainage complex. Indeed, if source controls can be of benefit in attenuating the impacts of urban runoff, what benefits might they have for a similar shift in the technologies of wastewater treatment from a centralized, end-of-pipe location to a host of distributed on-site (individual household) locations?

But perhaps more to the point of the present paper, how might the reliability of the city's wastewater infrastructure be altered by a move from end-of-pipe technology to source controls? Let us suppose there were to be separation of household sewage into its solid and liquid constituents on-site, i.e., at source, and cleaner industrial technologies. Together, these innovations might lead to the logical end-point of a city in which precipitation-induced runoff from the urban land surface, and the random failure of a multitude of spatially-distributed, small-scale pollution-prevention facilities, would be the only causes of impairment of receiving water quality (Beck, 1994). Would then the infrequent global failure of a centralized system employing end-of-pipe technology be more damaging to the environment of the city -- as a whole -- than frequent, multiple, localized failure in a distributed system of source controls? For we might have been able to restore the pre-city spectrum of precipitation-induced perturbations but to have lost the security of channelling all, local (and inevitable), accidental releases of contaminants to a site where they could properly be handled.

CONCLUSIONS

All systems are subject to a spectrum of dynamic perturbations, with low-frequency fluctuations over decades and years usually viewed as either long-term trends or quasi-equilibrium conditions. Against the background of these lower-frequency oscillations, each higher-frequency oscillation can be seen as a transient perturbation about an equilibrium. Strategies for managing water quality have hitherto sought to take action, i.e., defining regulations and installing infrastructures, to achieve an improved equilibrium at the scale of seasons and years. This is especially obvious in respect of removing and compensating for the introduction of a mid-frequency band of perturbations resulting from the diurnal and weekly habits of the population, industry, and commerce concentrated in urban centers. The convention has been to design wastewater treatment facilities and to allocate the assimilative capacity of receiving waters on the basis of assuming a steady state.

It is obvious that succeeding in such a strategy will allow greater attention to fall on the transient perturbations that are then observed to occur, and more dramatically so, relative to the improved equilibrium conditions. This success, coupled with the approach of a new millennium and the contemporary interest in sustainable cities, agriculture and forestry, has also promoted considerations of whither water quality management might be headed in the coming decades. In this light it is tempting to suggest that management should try to return the system to its "pristine" state and that this -- in some anthropocentric fashion -- implies the suppression of all disturbances of the system. Yet ecosystems have evolved in response to an entire spectrum of perturbations (Reice et al, 1990). It is not at all clear how the undesirability or otherwise of the various components of this spectrum should be established (in order then to guide the actions of management).

For some of these components, however, clarity of purpose can be achieved without great debate. Transient perturbations of water quality arising from infrastructure failure and precipitation events bearing abnormal substances, or abnormal amounts of substances relative to some location (or sector of the environment), are undesirable. While the significance of the latter has long been acknowledged, if not studied, the former has only recently emerged as a subject in need of more systematic enquiry. This is most notable in river basins that are now considered to have been successfully rehabilitated (as, for example, the Rhine; Malle, 1994). Monitoring systems for such purposes are tending towards being integrative in character, in order that the response of biota to a wide variety of potential contaminants can be detected. Early warning systems for pollution events are beginning to assume the same features as those of real-time flood forecasting and warning procedures (Puzicha, 1994).

Even where the desirability of taking action to suppress the occurrence and effects of transient events is clear, it is yet hard to escape the need to consider the broader issues noted above. For in trying to isolate the generic form of a singular, transient perturbation about an equilibrium condition, one is impressed by the way in which so many cross-spectrum effects are important. A high-frequency disturbance may provoke a transient change in the long term and the nature of the high-frequency response may change as a function of lower-frequency fluctuations. The goal of managing transient perturbations about an equilibrium might therefore have to be set within the strategic context of restoring the entire spectrum of the system's behavior to some quasi-pristine template.

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