Linking Health Concepts in the Assessment and Evaluation of Water Distribution Systems

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The concept of health is not only a specific criterion for evaluation of water quality delivered by a distribution system but also a suitable paradigm for overall functioning of the hydraulic and structural components of the system. This article views health, despite its complexities, as the only criterion with suitable depth and breadth to allow a holistic assessment of system performance. Although many decisions relating to the planning and design of water distribution systems do implicitly consider human health, engineers and planners seldom explicitly adopt a "health mindset" overall and, thus, miss the richness and possibilities of a health framework for a wider range of system evaluations, considerations, and trade-offs. This article argues why a breakdown in a healthy system will so frequently result in stresses experienced by humans and briefly reviews the concepts of human health and system health and provides specific examples of a significant interaction between the two.

Keywords: *health; water distribution systems; water quality standards; circulation*

To someone who has given the matter only casual thought, definitions may at first appear both trivial and obvious. From the time we were young we have learned an increasingly sophisticated system of classification, practicing distinctions continually until they become comfortable and acceptable, and probably unquestionable. Yet learning that dogs can be three legged and that wolves are not dogs, or that neither a whale nor a starfish are really fish, requires a subtle and flexible set of rules that is often beyond simple articulation.

Thus, when examined closely, many definitions turn out to be quite elusive, having a "difficult-to-articulate" property, an aspect that causes them to become vague and amorphous at the fringes of their intended or usual boundaries. Despite the importance of clarity, mathematics has long wrestled with specifying a consistent and concise definition for the concept of a *set*, biologists sometimes still argue about as basic a boundary as that between life and nonlife, and who now is brave enough to try and make exact distinctions between various shades of color, particularly in disagreements between individuals of different culture? Extreme postmodernists would perhaps abandon the whole exercise as futile and yet, the amazing thing is that a great deal of highly valuable communication is still possible between diverse individuals, and agreements and correspondences are a common enough occurrence to make even something as ambitious as an international conference both possible and rewarding. So even if the fabric of definitions does fragment a bit with the passage of time, needing the occasional patch or mending job, the overall exercise can bring both insight and satisfaction.

The current article explores the elusive and difficult concept of health, applying this concept both to the humans that use the water supplied via a water distribution system and to the system itself. The goal is to progress by analogy, reflecting that our human health is dependent on a variety of complex but interdependent systems that may or may not be present in the organization of a water utility. But more than this, the article argues that we neglect the health of the system that brings us water to our peril and that such neglect can threaten the very purpose for creating such an expensive and elaborate system in the first place.

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Preliminary Health Concepts

Living as we all have in our bodies for our entire life has no doubt given each of us an intuitive concept of health that probably involves ideas such as feeling well, being generally free from pain, and having no obvious diseases. The World Health Organization (n.d.) has stated that "health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (para. 1), and others have informally stated that health gives us a rewarding and not too painful experience. However, on reflection, such a set of attributes is obviously simplistic: Some of the worst and most dangerous diseases can progress silently without obvious symptoms until they are devastatingly lethal. Moreover, if one searches for the mere presence of latent disease in any of us, a whole catalogue of pathogenic organisms are probably resident within all of us at all times. Perhaps more controversially, pain turns out to be one of our most powerful feedback mechanisms, sometimes warning us to make adjustments now before more dire effects occur. The pain of a burn is not only a strong incentive to take our hand out of the fire, and to be quick about it, but also a pretty memorable lesson to be more careful with fire next time. Thus, dealing with the pain as a problem, and not the symptom of one, can be hazardous and trade an early warning signal for a full-blown problem. Turning off an alarm may well silence an annoyance, but it might also be the wrong action if the building is indeed on fire. As individuals, some of our most memorable, powerful, and in the long run useful lessons from life can in fact be the most painful in the short run.

The relationship that exists between microorganisms and our health is a particularly complex one. Countless trillions of bacteria coexist within us, being present in astronomical numbers on our skin and in our digestive system, performing a countless number of beneficial tasks, as well as occasionally causing disease. As Bryson (2003) so nicely summarized,

> Bacteria, never forget, got along for billions of years without us. We couldn't survive a day without them. They process our wastes and make them usable again; without their diligent munching nothing would rot. They purify our water and keep our soils productive. Bacteria synthesize vitamins in our gut, convert the things we eat into useful sugars and polysaccharides, and go to war on alien microbes that slip down our gullet. (p. 303)

This perspective is helpful to remember in the context of water distribution system design and operation. The goal of achieving chemically pure water, even waters supplied with a latent defense mechanism against further penetration by "foreign" powers, is perhaps an understandable and readily communicated simplification. Perhaps it is also a natural limit of an approach seeking the lowest common denominator between bacterial susceptibilities among people. For example, a recent *Opflow* article from the American Water Works Association stated the case as follows:

> In the aftermath of Sept. 11, 2001, many water system managers would have liked to install in their distribution systems a single device that would detect every imaginable contaminant. Unfortunately that silver bullet does not exist. Instead, drinking water surveillance is primarily attained through a combination of detection devices and water quality measures. These early warning systems can alert utilities to contamination events and allow operators to act quickly if water quality is compromised. (Whelton & Cooney, 2004, p. 1)

Thus, it is interesting that the sometimes-uncontested goal of producing chemically pure and uncontaminated water is not only ultimately unattainable but may be the ultimate contradiction in terms as well. As one example, if we are to be healthy, the bacterial populations that share our bodies must also be healthy, a requirement that may well cut across current water quality standards. Ironically, it has turned out that any attempt to achieve a sterile environment free from threats and biological attacks not only fails to make us healthy but also makes us both weak and vulnerable (Dubos, 1959). Clearly, the role of bacteria in a distribution system, for instance in biofilms (see LeChevalier, Cawthon, & Lee, 1998), is a complex one, but the issue of whether such organisms can or do play any kind of beneficial role is rarely considered.

So, the concepts of health are not to be defined and realized through simple and neat functional forms. It is generally inconceivable, even to most people who set the standards, that the kind of binary criterion that stipulates, for example, that water with a contaminant level below a certain threshold is safe and water with marginally more of the same substances is unacceptable, is defendable in the long run. Moreover, well recognized by those who set water quality standards are the difficulties that stem from assessment of human vulnerability, the breadth of chemicals that require assessment, the complexity of evaluating possibly synergistic chemicals, the difficulty of measurements and mitigation strategies, and a host of related challenges.

By contrast to this, a more holistic view of health requires a kind of dynamic balance between the internal response mechanisms that our bodies and minds can bring to bear on a stimulating and challenging environment where the threats challenge us to respond but do not overwhelm our system through the speed, duration, or intensity of the required response. This requires a more complex assessment of demands and challenges that typically arises when we discuss drinking water standards; what we need is to take into account the overall resources and requirements of the system, including the range of susceptibilities and resistances of the individuals using it, while all the while we consider the nature of the environmental or external challenges imposed on us. Thus, biologically, health necessarily involves conditions favorable to the organism as a whole and the ability to mount an active defense against homeostatic processes.

Of course, none of this will be easy. Health concepts have an individual adaptability and mutability that complicates assessments and defies many simple-minded generalizations. But the reality is that we make such assessments every day in almost every activity. What we demand from a sport or recreational activity is to be able to come to a rapid and personal evaluation of benefits and costs and then to make up our own mind. What we do not want are hidden faults and difficulties and surprises when they suddenly arise. And in this respect, water professionals may at times need to be more direct and honest, not making categorical and sometimes-unsubstantiated claims that a certain water is fit to drink. Instead, water professionals need to state clearly and directly that as with any other human action, there are risks, and then they need to find clever ways of comparing the risk of participation in an open utility with the risk of not doing so. Certainly the risks are very real. The loss of life and economic costs of contaminated water will not go away simply because the assessment and mitigation of conditions represents a complex problem.

In this regard, it is worthwhile and interesting to comment on the importance of stability in the environment in which health is assessed. Sudden changes in environmental stress are a well-known trigger of deteriorated health and of our various defense mechanisms to respond to challenges. In an analogous way, sudden changes in water systems often cause physical, chemical, and biological disturbances in the system itself. Transient events, whether red water events or the possibility of intrusion, are physical changes often triggered by sudden changes in system operation, in the same way that disease is often triggered by sudden changes in environmental or external loads. An older, although still relevant, passage in Dubos (1959) has a wonderful double meaning in this context:

> Fitness to the total environment being essential for health in the Hippocratic view, it follows that disease almost inevitably ensues when changes in conditions are too rapid and too violent to allow adaptive mechanisms to come into play. Time and time again Hippocrates comes back to the dangers entailed in sudden changes of any sort. (p. 119)

Healthy System Concepts

Having set the stage, a few connections between systems and organisms are immediately obvious. From this perspective, the concepts of a healthy system can also be viewed as a logical extension of the concept of the health of an organism. This thought leads to a set of reflections that have considerable value.

An Enfolded Whole

Bill Vanderburg (2000), in his profound reflection on technology and its impact on our lives, speaks of biological systems as being "enfolded" in the sense that each part of the system contains a kernel of the whole. Biologically, each cell contains the same DNA coding that is responsible for creating the structure of the whole organism.

No mechanical system is enfolded in this sense, because the parts come into being from separate and distinct processes with independent instructions. And yet, perhaps at the level of organizational control, the human parts of the system would likely benefit from a greater degree of enfolding. If the work crews that maintain valves, that repair pipes, and that respond to leaks were consistently valued for their contribution to the whole system, and if they knew the key parts they play in contributing to the health of a whole community, might they not do their tasks with greater pride, care, and diligence? If the politicians that set municipal budgets and the voters that gave them their mandates had something as direct as a nerve connection to know when the system was languishing, would as many shortsighted decisions be made?

Few of us want to live meaningless lives, and a community contribution through a job well done, that is understood and valued by both superiors and by the community served, is a notion of enfolding that appears ideal. But the degree of this cooperation that is required for the survival of any complex multicelled organism is an inspiration and concrete example that perhaps makes this goal as tangible as it is immediate.

Multiobjective Thinking

Health is too large a concept to be forced into a single mold or evaluated with a single index. No one would be foolish enough to think that the only requirement of an annual physical is to take a person's pulse or to feel that the only ingredient necessary for health is taking vitamin pills. Healthy organisms must balance the needs for rest and exercise, for sleep and wakefulness, and for periods of eating and times for digestion. Nesse and Williams (1994) brilliantly made the point that our defense and immune systems are compromises reacting to a variety of functional requirements. For instance, they argued that we could not adapt to certain challenges only at the expense of being more vulnerable to other attacks or demands. As one example of many, if our legs were stronger and less liable to break if we fell, we might be slower and less agile and more inclined to be caught and eaten!

Yet in the water distribution context, we seem to more readily forget these inherit compromises. A water distribution system is also a set of pragmatic trade-offs between different threats that sometimes push us as designers in different directions. An obvious example is the choice of pipe diameter; the larger the diameter, the better our protection from fires in the system; but the longer the residence time, the more vulnerable the water is to biological invasion (Filion, Karney, & Adams, 2004). We cannot have it both ways, any more than the person who rides a bike can ensure that improvement in the vital capacity of his or her lungs will more than offset the chance he or she will be hit by a passing truck. Individuals require the freedom to make their own assessments of risk and payoff, and the public forum has evolved to make such choices. In the water distribution system context, it is important to start to present the data and framework to make such trade-offs visible and meaningful.

Smart Systems

If one reflects in any detail about the configuration of health systems, perhaps the most amazing aspect of them is how clever they appear. The interconnections between structural support, maintenance or long-term connections and adaptability and response are remarkable. As in water systems, single components seldom serve one purpose alone, but biological systems have taken this design framework to levels far beyond our simple designs. It is reflections on issues such as this that have perhaps so profoundly motivated areas of design known as *biomimicry*, which seeks to use nature as not only a model for human design but also a measure and mentor (see Benyus, 1997).

In this context, consider what Nesse and Williams (1994) said about bones; but as water engineers, we might perhaps think also of the possibility of pipes:

> The body's simplest structures reveal exquisite designs unmatched by any human creations. Take bones. Their tubular form maximizes strength and flexibility while minimizing weight. Pound for pound, they are stronger than solid steel bars. Specific bones are masterfully shaped to serve their functions—thick at the vulnerable ends, studded with surface protrusions where they increase muscle leverage, and grooved to provide safe pathways for delicate nerves and arteries. The thickness of individual bones increases wherever strength is needed. Wherever they bend, more bone is deposited. Even the hollow space inside the bones is useful: it provides a safe nursery for new blood cells. (p. 4)

It is interesting to imagine the systems we might create were we to think of pipes not only as conduits of water but also as adaptive, responsive, and effective corridors of information and connection.

Some Direct Connections

Having considered some perhaps less obvious links, it is worthwhile to develop some more direct interactions between system and human health. There are perhaps endless ways of trying to make these connections, ones focusing on specific systems and functions. A few obvious examples are included in the following discussion.

System Aging

One of the obvious connections between pipe systems and human systems is at the level of the circulation system. As both pipes and arteries age, there is a strong tendency toward a deposition on the conduit wall, leading to higher losses (and, thus, higher blood and system pressures), a tendency to leak or bleed, and an increased load on the pump (or heart). Moreover, as human exercise can be a way of resisting deposition, of removing blocks and restrictions, so system flushing can work in a similar way in water networks.

In the human health case, there is an obvious tendency for systems to bruise or bleed more easily, and this must be countered by greater vigilance to avoid undue stresses; so too in the water distribution case, where older systems must be operated more carefully or they are liable to leak or break. A greater need with aging for more nutrient support in the form of vitamins and supplements could perhaps be compared to a need for greater injections of chlorine and more thorough treatment as a distribution system ages (Clark & Grayman, 1998). (It is perhaps prudent to leave off direct comparison to changes in mental processes with aging and the creation of rigidity and stubbornness that sometimes characterizes utility decision making!)

Pumping Capacity

A heart is a highly sophisticated biological system for maintaining flow and pressure in our circulation system. As anyone with a recent heart attack might attest, its role and function is forgotten to our peril. Remarkably, water distribution system pumps are commonly neglected and taken for granted in much the same way, with scheduled maintenance and diagnostics often neglected under the specter of short-term budget pressures, as we often fail to get adequate exercise under analogous circumstances. Without proper attention and considerations, pumps and hearts are both liable to fail or complain exactly when their service is required the most, which is pretty much all the time. It is not difficult to make connections to larger issues such as stress tests in humans and an inverse transient calibration of a water distribution system. Or to show that borrowings can go in either direction, it is interesting to point out that a heart bypass operation is really nothing more than what municipal engineers have been practicing for years—a way of "looping" the pipe network to increase flexibility and decrease losses.

There is an additional and interesting connection here that is worth mentioning as well. The power supply for the human heart is actually fed by the heart itself, as the heart muscle is supplied with blood for its own purposes through the coronary artery. If this artery becomes blocked or clogged, the heart is starved for power and unable to continue its own proper function, with sometimes disastrous consequences. In a similar way, if the power to a working pump is cut, the resulting power failure event can have repercussions that are profoundly important to the system as a whole. Is it possible that surge protection systems would get better recognition from decision makers if the analogy with a heart attack were more commonly applied? Regardless of the answer to this question, what is clear is that we tend to take both pumping stations and our own hearts for granted until we receive sometimes-forceful reminders of the crucial roles they play in system performance.

System Assessment

Our bodies maintain a phenomenal set of transducers and relays that are constantly assessing system status and passing this information back to "central command." The delicacy of our nerves, eyes, sense of smell and taste, and sense of touch and hearing transmit a bewildering array of signals throughout the body. This information is tied in directly to functions of decision support, memory, motor control, and action; it is not simply stored and immediately forgotten, nor is it stored in irretrievable files in arcane formats (as too much supervisory control and data acquisition system [SCADA] data are!). Modern SCADA design could learn many lessons from the elegance and flexibility of such a support and assessment system, and perhaps interface design might eventually benefit from a set of readouts that are oriented mostly to our eyes. Important signals in our body tend to get our attention in a great many ways, and many of these are compelling and virtually irresistible.

Systems Thinking

What is needed progressively more in this framework is the connection between system operation, system behavior, and likely health effects. Only in this way can there begin to be a set of links that move backward from a desired health outcome to the kind of investment needed in system hydraulics or infrastructure to influence this outcome.

For example, it is progressively accepted that hydraulic transients are capable of generating significant negative pressures in water systems and that these pressures have the potential to cause intrusion of contaminated water from the environment into a pipe (Fernandes & Karney, 2004). A recent article by McInnis (2004) expands the consideration of these transient-intrusion events from their purely hydraulic aspects to take the first steps toward developing a risk-based framework for comparing the relative risk reduction achieved by alternative transient-intrusion mitigation strategies. The alternative strategies considered by McInnis include a variety of combinations of changes to system operation and surge controls, measures aimed at reducing the potential for contaminant intrusion from the soil-groundwater environment near the pipe. A reference groundwater contamination is assumed, and intrusion volumes and time-varying pathogen concentrations are computed, respectively, using hydraulic transient and water quality models. Risk-based measures should be evolved in many areas to provide quantitative assessments of the relative reduction in the risk of receptor infection or illness achieved by alternative mitigation strategies or investments. It is exactly this kind of thinking and groundwork research that is called for by making the link between system health and human health explicit.

System Connections

That the link between system and human health exists is something that few argue. That the link is perhaps more profound than we usually consider may also be readily acknowledged. However, the extent of and the human misery associated with this connection are quite difficult to overestimate.

An interesting and rather disturbing case is currently being traced in Canada, and the core scenario is worth relating; because the specifics are a subject of a court challenge, the details have been shifted to the ground of a possible connection rather than an established set of facts. However, the issue at hand is that infrastructure repair work may well have caused interior pipes in an older house to begin leaking, as a result of shock waves from nearby blasting in the subsurface. These initial disruptions may have caused some structural damage and warranted expensive repair. However, of far greater importance in this case is the fact that the new moist environment behind the walls may have allowed a dangerous and highly toxic microorganism to rapidly grow and multiply, causing severe illness and significant personal suffering to those in the house. Moreover, the repair costs for the damages with this change now escalate considerably, because removing the "bug" from the house requires either a huge expense or partial demolition of the structure.

We should be thankful that such cases appear to be rare. But how rare they are depends greatly on how accurately we can diagnose, or are even alert to, the sometimes-tortuous chain of events that connects cause and effect. The point here is that linked events will interest us more, and concern us more deeply, if we think of health more generally and not simply reassure ourselves with simple lines of legal responsibility. The issue in intervention is surely to be able to tie in what we do as engineers, designers, and operators to what are the human (both economic and health) impacts or consequences of these actions. Eventually, we must also look beyond the specific systems in question and realize that healthy cities, healthy communities, and healthy environments are inextricably linked.

Conclusion

When faced with complex challenges, it is easy and understandable that we seek ways of simplifying the problems into something more manageable and tractable. But clearly there are dangers in this, because the original problem and challenges can be lost and substituted from what is of less value. In the case of water distribution systems, we have often thought of these as collections of individual pipes and forgotten our nobler calling as key contributors and maintainers of the health care system of society. But health care systems require intellectual and emotional engagement as well as a delicate set of balances, one that requires not just technical skill but also a great deal of wisdom to engage and adjust. We, as engineers, have shown ourselves equal to many of the technical challenges of the past, but new requirements and demands face us daily, and it is perhaps time to question not simply our tools and the problems they endeavor to solve but also the framework we adopt and the places we return to for inspiration. In this context, the delicate and marvelous health and support systems that comprise our own bodies deserve our attention and regard, and perhaps also our imitation.

References

Benyus, J. M. (1997). *Biomimicry: Innovation inspired by nature*. New York: Quill/William Morrow.

Bryson, B. (2003). *A short history of nearly everything*. Toronto, Canada: Doubleday.

Clark, R., & Grayman, W. (1998). *Modeling water quality in drinking water distribution systems*. Denver, CO: American Water Works Association.

Dubos, R. (1959). *Mirage of health: Utopias, progress and biological change*. New York: Anchor.

Fernandes, C. V. S., & Karney, B. W. (2004). Modeling the advection equation under water hammer conditions. *Urban Water Journal*, *1*(2), 97-112.

Filion, Y., Karney, B. W., & Adams, B. J. (2004, December). *Multiobjective design of water networks with random loads*. Paper presented at the 4th International Symposium on Environmental Hydraulics, International Association of Hydraulic Engineering and Research, Hong Kong.

LeChevalier, M. W., Cawthon, C., & Lee, R. G. (1998). Inactivation of biofilm bacteria. *Applied Environmental Microbiology*, *54*, 2492-2499.

McInnis, D. M. (2004). A relative risk framework for evaluating pathogen intrusion in distribution systems. *Urban Water Journal*, *1*(2), 113-118.

Nesse, R. M., & Williams, G. C. (1994). *Why we get sick: The new science of Darwinian medicine*. New York: Vintage.

Vanderburg, W. H. (2000). *The labyrinth of technology.* Toronto, Canada: University of Toronto Press.

Whelton, A. J., & Cooney, M. F. (2004). Drinking water surveillance: We need our customers to complain. *Opflow*, *30*(11), 1.

World Health Organization. (n.d.). *WHO definition of health*. Retrieved from http://www.who.int/about/definition/en/

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