SUSTAINABILITY: Life, Liberty and the Pursuit of Negative Entropy - Part I

By John Milne

Happiness will follow.

Clark County's approach to stormwater management over the years has differed significantly from that of the Washington State Department of Ecology. Where Ecology has focused on controlling runoff flows from new development, Clark County's efforts have instead been targeted at restoration of the natural watershed hydrology. This county focus led to a search for holistic, watershed-based solutions that mimic natural systems. The governing principle by which the county mimics natural hydrologic processes has been loosely termed "entropy-based watershed management." This article introduces this organizing principle for the management of watersheds and other natural resources, and suggests how use of this strategy might contribute to future sustainability efforts.

Entropy-based watershed management: holistic, watershed-based solutions that mimic natural processes

"Instead of engineered stormwater facilities, why don't you use holistic, watershed-based methods that mimic natural processes?" This criticism was leveled at the county during the development of their mid-'90s watershed plans. "Mimicking" something might initially seem to be a backward step from developing sophisticated computer models. However, when trying to achieve basic engineering objectives, attempting to mimic natural processes does appear to make sense:

- Natural processes are highly efficient; mimicking them could be very cost-effective.
- Natural processes seamlessly interact and work across physical, chemical and biological boundaries; they are truly holistic.
- All natural processes are very efficient, not just the one your program is focused on at the moment but all "downsystem" processes that follow.

So a strategy that utilizes and mimics natural processes may show promise for effective resource management. But what does "mimicking a natural process" mean, in physical terms? The premise behind the county strategy is that natural systems always act to minimize energy loss and so leave each resource in its highest, most ordered thermodynamic state, i.e. in a state of minimum entropy, after each process has been completed.

This physical concept of minimizing entropy at all times seems to encapsulate how natural systems operate across physical boundaries for the efficient capture, storage and frugal use of energy and natural resources. At heart, an entropy-based resource management strategy is an attempt to *create and maintain order* in all aspects of resource management, from the molecular level to large-scale ecosystems. "You need to create negative entropy, Dad" is how my biologist advisor puts it.

Natural examples

If this contention is to be correct, a natural system that manages a resource perfectly would, after every process has taken place, leave that resource:

- In its highest state of matter, i.e., solid phase.
- In the highest energy state, i.e., potential energy.
- At the highest level of potential energy possible.

That system and similar systems would also be expected to be ubiquitous in nature.

Is there such an example in the natural world? Let's take as the resource the annual rainfall that falls on a watershed:

- What is the most ordered state (least entropy) for water?
- Would working to establish and maintain the annual rainfall in that state constitute effective management of the resource?
- Is that state seen prominently in nature?

Snowpack

Snowpack along watershed ridgelines is water in solid phase with the highest possible potential energy. All watershed

Snowpack

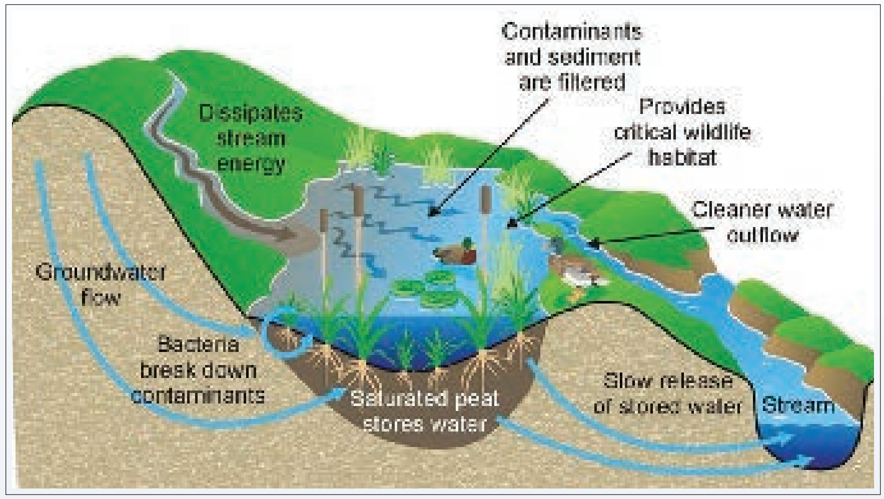
CLICK HERE TO RETURN TO INDEX

managers know that a good snowpack means a good year for the watershed and everything in it; it constitutes very effective, holistic management of the annual rainfall supply.

However, from a management standpoint, physically creating snowpack from rainfall, by cloud-seeding or other methods, is beyond the means of most communities. So what might the next best thing be?

High groundwater is water in liquid phase with high potential energy. As seen in the above graphic, maintaining high groundwater elevations can be expected to conserve water effectively as well as produce multiple additional environmental benefits.

Now we have something that a watershed manager might be able to use. A simple entropy-based governing principle for effective watershed management might be to promote the establishment and maintenance of high groundwater elevations in all regulatory, planning and capital construction activities that the watershed manager can influence.



Watershed benefits of high groundwater

Holistic watershed management and downsystem processes

Before presenting a Clark County example of entropy-based watershed management, it's worth lingering on the additional benefits that may occur if resource management focuses on a fundamental driving process. For an example of holistic natural resource management dear to (some) engineers' hearts, consider the case of single-malt scotch whisky. Most scotch aficionados will tell you that it is the water used in the distilling process that gives each whisky its individual flavor, far more than any transcendent distilling skill. Take a trip to the Glenmorangie distillery in Tain, Scotland. The water in the burn looks like Coca Cola as it tumbles over the rocks and black as molasses in the pond at the distillery. And Glenmorangie has a very peaty smell and flavor, which many people like. Would they enjoy it as much if we engineers had captured and piped all that "pure" highland rainwater all the way to the distillery? Apparently the glens know better than we do how to make good whisky, and maybe what's best for that glen's salmon run also.

This example shows that using and mimicking this natural management of the water resource has the potential to move beyond meeting minimum state standards for beneficial uses into preserving all the attributes of each individual stream; maintaining each stream's "signature."

Clark County Amphitheater Sub-basin Retrofit Plan

This recent work effort is one example of the county's use of entropy-based watershed management as an organizing principle for rehabilitating watersheds. Here the principle was expressed as a generalized game plan to "pump up the groundwater as high as possible then plant everything." The Amphitheater plan accomplished this in several simple steps:

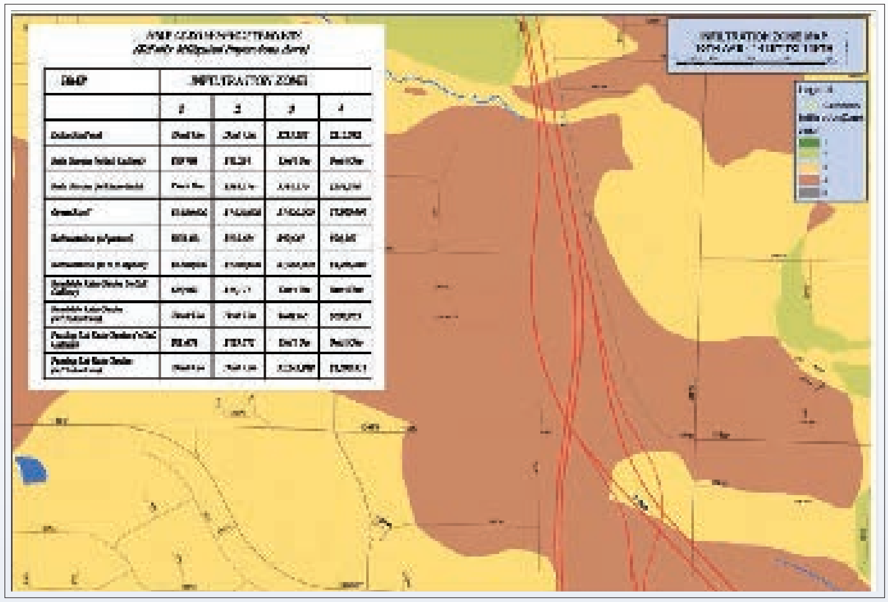
Step 1: Develop Infiltration Zone Mapping and Matrix

The county's old Infiltration Zone maps and matrix were updated to add newer LID infiltration BMPs as well as list each BMPs cost-effectiveness in terms of their cost per "Fully-Mitigated Impervious Acre" (the basis of the county's "hydrologic accounting" procedure).

Step 2: Site the most cost-effective infiltration BMP everywhere possible in the sub-basin

Starting at the top of the basin and working downstream, the Infiltration Zone maps and matrix are used to site the most cost-effective infiltration/retention BMP at every feasible retrofit location. This process results in Sub-basin Plan Alternative 1, the standard "Maximum Improvement" alternative.

The above plan excerpt shows several common LID BMPs such as rain gardens, eco-roofs and retention ponds, with adjusted controls on the existing detention ponds as the furthest downstream "BMP of last resort."



Infiltration Zone map and matrix

However, by requiring ourselves to "pump up the groundwater as high as possible," we must also re-establish the natural drainage paths and headwater wetland in this area, and add trench dams to storm sewer and utility trenches. Those measures go beyond standard water quality treatment and flow control design and harken back to the county's old strategy of restoring the natural watershed hydrology. Only now we are doing this in a more systematic and quantified way.

Step 3: Alternative Analysis; Phase 1

Here, additional Plan Alternatives are developed simply by reviewing the hydrologic accounting summations and deleting the least cost-effective individual BMPs. This quickly identifies two or three candidate Plan Alternatives for more detailed analysis.

Step 4: Alternative Analysis; Phase 2

In this final step, hydrologic and hydraulic models (WWHM, HECRAS) are used to model the remaining plan alternatives in more detail and as systems rather than as a collection of individual BMPs. The HECRAS sediment-transport module is the basis of the county's "hydraulic accounting" procedure, which uses a single-reach idealized stream channel to evaluate the annual erosion resulting from output hydrographs from the candidate alternatives. The Plan Alternative that generates and exports the least annual sediment mass within the available budget wins.

The Clark County Amphitheater Sub-basin Retrofit plan demonstrates that an entropy-based watershed management concept can be used as an organizing principle for developing effective watershed rehabilitation strategies. It requires you to:

- Focus on primary causes rather than effects.
- Use top-down management, i.e., intervene as soon as possible after rainfall hits the ground and do everything possible at each succeeding step.
- Consider watershed needs outside your immediate program objective.
- Develop cost-effectiveness metrics for all BMPs and Plan Alternatives.
- Include improvements that may be difficult to quantify and for which you may not understand fully all the natural processes at play.

The county has also used this strategy on other work products, including:

- The hydrologic and hydraulic accounting procedures were used to identify, screen, design and build numerous stormwater/watershed rehabilitation projects.
- Restoration of the natural drainage patterns and groundwater recharge in a degraded headwater wetland using a watershed water balance approach.
- Development of a sustainable land use plan serviced by a sustainable roadway grid.
- The successful defense of a county road project against a legal challenge that the increase in impervious area would reduce groundwater recharge and impact wetlands.

Summary

This article has introduced the concept of entropy-based resource management as an organizing principle to develop sustainable ways of managing watersheds and other natural resources. Outcomes from Clark County's use of this strategy have been successful to date, and the strategy is expected to be consistent with Ecology's recent move towards using LID techniques as well as future groundwater recharge and stream base flow initiatives and recovery efforts for endangered salmon. Upcoming articles in this series will describe county work products in more detail and suggest how use of this broad strategy might contribute to future sustainability efforts.

Sub-basin Plan Alternative 1: Maximum Improvement

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Part II - Entropy-based Watershed Management

A previous article introduced this organizing principle and provided a recent county example of its use. This second article explains more about its development and presents additional examples. The third and final part in this series will expand this concept to the management of other resources, and offer suggestions on how this strategy might contribute to future sustainability initiatives.

Background: Stormwater management and watershed rehabilitation in Clark County

Clark County's approach to stormwater management over the years has differed significantly from the Washington State Department of Ecology. The county's first stormwater ordinance in 1994 moved beyond Ecology's flow control focus to address other watershed issues such as groundwater recharge and stream base flows. That ordinance required mitigation for the increased volume of runoff from new development. It also required no loss of surface storage volume in the flood plains of all streams, not just in mapped flood plains.

In their watershed planning and capital program work, the county's efforts aimed to restore the natural watershed hydrology in disturbed watersheds. The 1994 Upper Burnt Bridge Creek Watershed Plan proposed closing off the existing ditch draining the large headwaters area. An expanded Burnt Bridge Creek Watershed Plan the following year mapped historic wetlands within the watershed and developed a natural condition hydrologic model, both acting as targets for watershed rehabilitation strategies. That plan also introduced mandatory roof drain infiltration as well as roof drain retrofit projects in suitable areas of the watershed. The 1998 Salmon Creek Watershed Plan used a runoff volume reduction strategy of "infiltrating clean stormwater runoff wherever possible without causing problems," and developed Infiltration Zone maps and an Infiltration BMP-selection matrix to help achieve this objective.

These county efforts and others came to be grouped under the general organizing principle known as entropy based watershed management, introduced in the previous article. Some more examples of county work products using this strategy follow.

2008-2012 Stormwater CIP; Grassland Meadows Stormwater Facility Retrofit Project

The county's hydrologic and hydraulic accounting procedures were used to identify, screen, design and build numerous stormwater mitigation and watershed rehabilitation projects over this four-year period. The Grassland Meadows project replaced an older biofiltration swale/detention pond with a new rain garden/retention pond. This design

2008-2012 Stormwater CIP: Grassland Meadows Stormwater Facility Retrofit

approach, where existing detention ponds are replaced with infiltration/retention facilities, is typical of projects that score high on the county's hydrologic accounting measure, and is also consistent with the county's generalized effort to increase groundwater elevations throughout the watershed wherever possible.

The project took advantage of low but significant infiltration rates in the bottom of the existing detention facility as well as an extra foot of available surface storage to greatly improve the flow control provided by the facility while also enhancing groundwater recharge.

In addition to identifying cost-effective CIP projects, the hydrologic accounting computations were also used to assess the effectiveness of pre-and post-project flow control within the basin.

The graphic shows this catchment area to be approximately 50% mitigated to today's flow control standards. Based on that measure, further flow control improvements would not be a priority for this area.

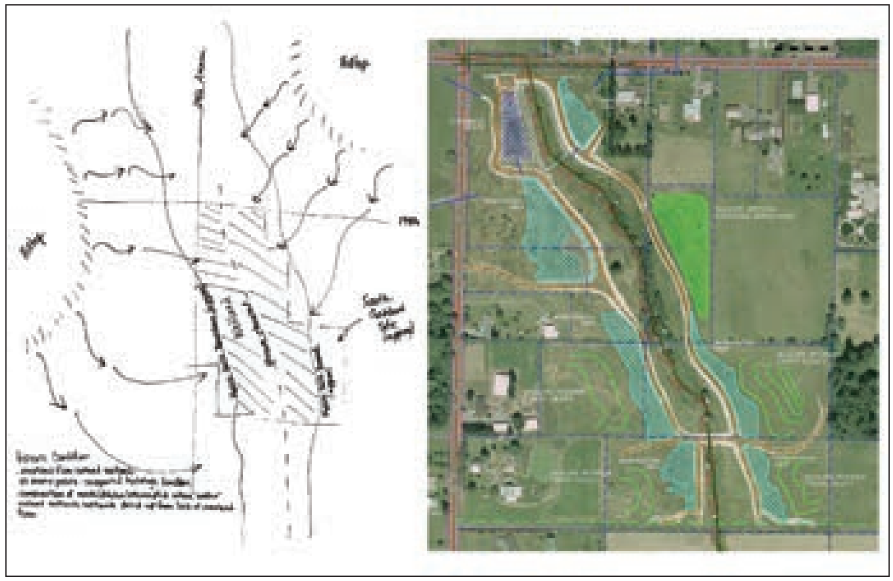
West Mill Creek Headwaters Enhancement Project

This project, currently under design, restores the natural drainage patterns and groundwater recharge in a degraded headwater wetland.

The project is a good example of how watershed planning and stormwater and wetland capital projects have traditionally proceeded in Clark County. The county tries to determine how the natural hydrology worked then put everything back that same way. Here we are reversing the ditching that has been done in this headwaters area in the past.

The entropy-based resource management principle here was simplified to re-establishing and maintaining groundwater elevations as high as possible, then reforesting the whole site. The project design was based on an annual watershed water balance computation rather than standard flow control design. Early modeling results showed that the project would recharge an additional 11 acre-feet annually and increase stream base flows by 30% through the summer months.

Fully mitigated flow control area, Grassland Meadows catchment



West Mill Creek Headwaters Enhancement Project

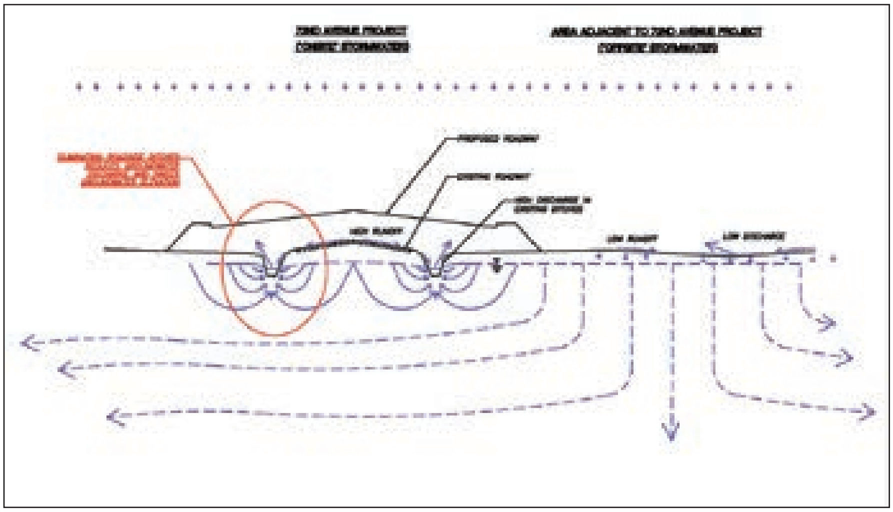
NE 72nd Avenue Road Project

This is a slightly different example of using this organizing principle as a framework for viewing watershed issues. Though this issue didn't arise from a watershed management activity, use of this organizing principle helped the county with an important legal defense.

In this case, two important county road projects and one large watershed project were threatened by a third-party lawsuit which claimed that, by paving over an expanded right of way area, a road-widening project would reduce recharge and so dry up wetlands in the area. If you are accustomed to viewing watershed issues from an entropy-based watershed management perspective, an answer to this difficult SEPA contention readily comes into view. Recall that the county's main watershed objective is to keep the groundwater at as high an elevation as possible, not just to promote recharge. A question to ask is "what does recharge do directly for wetlands, streams, etc.?" Isn't the elevation of the groundwater table (water in liquid phase at the highest possible potential energy) the only thing that matters, regardless of how that elevation came to be? The simple graphic below showed that, by filling in existing ditches, the county road project would eliminate an existing groundwater discharge and so raise groundwater elevations to have a net positive effect on the regional groundwater and wetlands.

Sustainable Land Use Plan

This last example is a simple graduate school term paper, which nonetheless led the county to draw some important watershed management conclusions and identify some potentially highly effective capital improvement projects. Recognizing that regulations, capital improvement projects, and even watershed plans have been only partially successful in preventing watershed degradation, this term paper proposed using the land use planning process as a potentially more effective intervention point. The Cougar Creek basin, an urbanized basin tributary to Salmon Creek, was used to develop a



E 72nd Avenue Road Project; elimination of ditch discharges.

sustainable land use plan based on water resources.

The plan was developed in several simple steps:

Step 1: *Current comprehensive plan*
The first map shows the current land use plan, mostly econometric and transportation-based. The goal is to try to develop a new plan with the same mix of land uses but distributed throughout the watershed in a way that will produce less impacts, cost less and be more sustainable.

Step 2: *Use a groundwater flow model to determine the best watershed arrangement of land uses.*
The assumption here is that the most sustainable land use arrangement will be the one that produces the highest groundwater elevations throughout the watershed. This is the same strategy as "pump up the groundwater as high as possible," but now quantified and modeled.

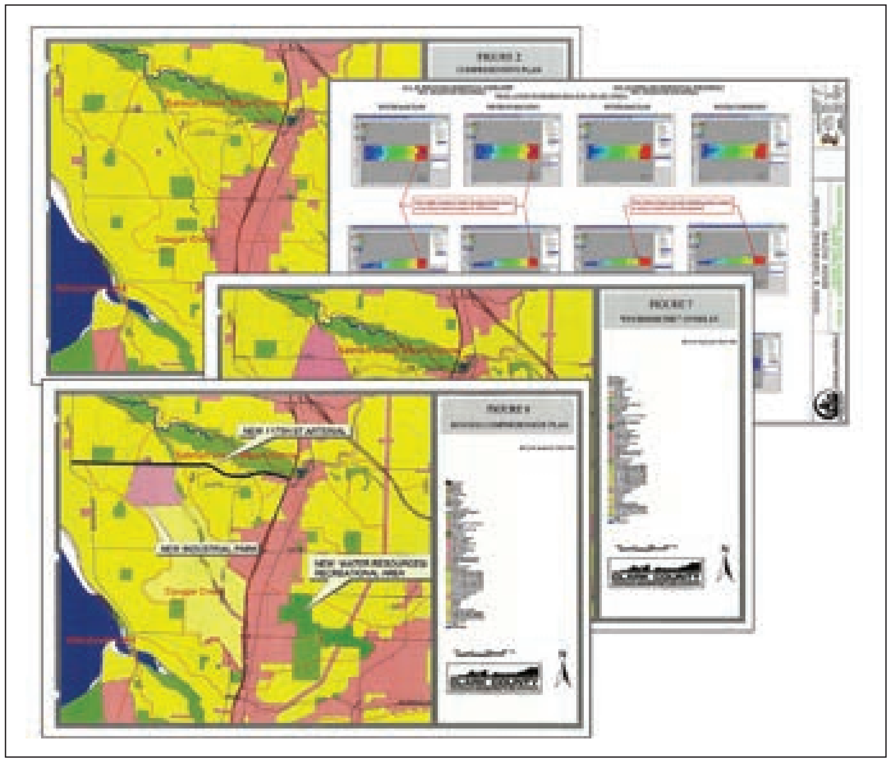
The method is to:

- Assign groundwater recharge and discharge values to Industrial/Commercial, Residential and Parks/Open space land uses.
- Place each of those three generalized land uses in the upper, middle or lower portions of the watershed.
- Analyze alternative land use placements using a groundwater flow model to compute the resulting groundwater elevations.
- Determine the optimal arrangement of land uses, i.e., the one which produces the highest groundwater elevations.

Step 3: *Envirometric overlay*
The envirometric overlay is developed based on the outcomes from the groundwater model, and sites land uses where they would maintain the highest groundwater elevations throughout the watershed. The solution worked out to be Residential at the highest elevations, Parks in the headwaters and valleys, and Industrial/Commercial in the lower watershed (but above the valley floor). Basically, place the land uses with the most net recharge in the highest locations in the watershed and avoid adding new groundwater drains.

"Use of an entropy-based watershed management strategy has led to subtle but important changes to Clark County's watershed management operations."

Step 4: *Sustainable land use plan*
The last map is a simple compromise between the original comprehensive plan and the envirometric overlay. It shows the final revised zoning plus some associated new infrastructure. In this instance, there is not that much change; because I-5 is a critical north-south transportation corridor, that need generally governs. However, some industrial development has been moved to a different location in the lower watershed, served by a new roadway arterial. And several small parks have been combined into one large regional park, sited to protect the headwaters area.



Development of a sustainable land use plan.

Summary and conclusions
Use of an entropy-based watershed management strategy has led to subtle but important changes to Clark County's watershed management operations. While Ecology's recent move towards LID techniques has brought state and county stormwater strategies closer together, the county's approach extends this strategy to what can be considered to be "LID on a watershed scale." Instead of being the constant focus, flow control is recognized as just one important technique for watershed protection and restoration, and the importance of maintaining or supplementing surface water and groundwater storage is equally emphasized. The need for headwaters protection and restoration is recognized, and trench dams are used as a cheap but effective watershed retrofit in high groundwater areas.

The county strategy has also been useful in a broader, organizational sense. Where watershed plans have often been held to be an essential precursor to effective watershed management, the county strategy also allows the development of more targeted and faster-implemented sub-basin retrofit plans for watershed rehabilitation. Looking to the future, an entropy-based watershed management strategy also suggests that the development of sustainable land use plans may be more effective than watershed plans in preventing watershed degradation in the first place.

SUSTAINABILITY:

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Part III: Entropy-based Resource Management and Sustainability

By John Milne

Clark County's approach to stormwater management and watershed rehabilitation has focused on restoring the natural watershed hydrology using entropy-based watershed management. Previous articles have introduced this organizing principle and provided some county examples. This final article expands this concept to the management of other natural resources and suggests how this strategy might contribute to future sustainability initiatives.

Entropy-based resource management

Clark County has many responsibilities beyond stormwater management. If entropy-based watershed management can be a useful organizing principle for managing water resources, might a similar strategy be useful for managing other resources such as energy?

Consider the difference in traffic flow patterns between a roundabout and a signalized intersection. At a roundabout, a car moves through the intersection without stopping. At a traffic intersection stop light, the car engine is running and using fuel, but the car is not going anywhere. This is an unnecessary and unproductive increase in entropy; an entropy change from a liquid with high potential energy to a gas with high kinetic energy. If we next note that energy use may be more related to corridor travel *time* (i.e., the time the car engine is running) than maximum design *speed*, we may be able to develop a more energy-efficient roadway grid by changing the design focus to minimizing the average corridor travel time. This can potentially be achieved by replacing a series of traffic signals with a roundabout corridor that allows continuous traffic flow without forced stoppages.

Postulating that the reduced entropy in a roundabout corridor may lead to a more energy-efficient roadway grid is sufficient in itself as a hypothesis to be investigated. However, this example also offers an opportunity to mimic a natural system to try to find a more sustainable design. To minimize the entropy in the system, we can suggest that the design of an energy-efficient roadway grid would attempt to develop the most *orderly* flow of traffic, and try to find an appropriate analog that will effectively represent the traffic flow process and suggest a solution. Consider the cars in a morning commute to act like molecules moving within a substance:

For the roundabout, traffic moves in a well-ordered manner, like a liquid. For the signalized intersection, traffic flow is more disrupted, disorderly and random; more like a gas. Liquid is a higher-order physical state than gas; mimicking a liquid should result in better resource management than mimicking a gas.

So, using an entropy-based resource management approach in two different ways to try to develop a more energy-efficient roadway grid, we arrive at the same suggested solution; use roundabouts at every opportunity rather than standard signalized intersections. Note the simplicity of this proposal from another viewpoint. We've been trying for many years to design cars that use less energy per mile; shouldn't we also design our roads to do the same?

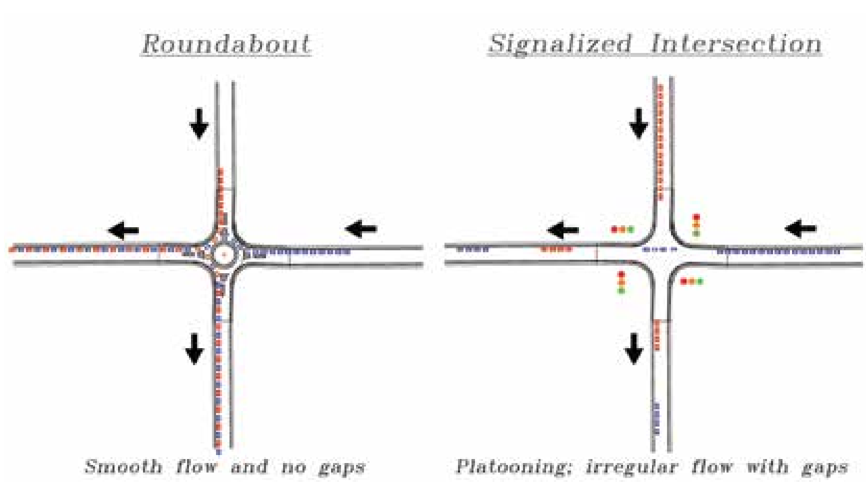
Sustainable roadway grid

The entropy-based resource management strategy can be extended one crucial step further to assess what might be the most sustainable roadway grid system to service (say) a sustainable land use plan.

Nature works very efficiently on *all* systems at the same time. We can also mimic this *holistic* feature of natural systems; we can walk and chew gum at the same time. The last example showed how we could design our roads for more sustainable use of energy; can we also promote sustainable water resource management at the same time? This is easily done; we simply combine a roundabout corridor with a green-street roadway design.

The roadway grid now combines the most sustainable energy use design with the most sustainable water resources design. With its frugal use of both energy and water resources, this now represents a

Traffic flow; roundabout vs. signalized intersection



Sustainable roadway grid

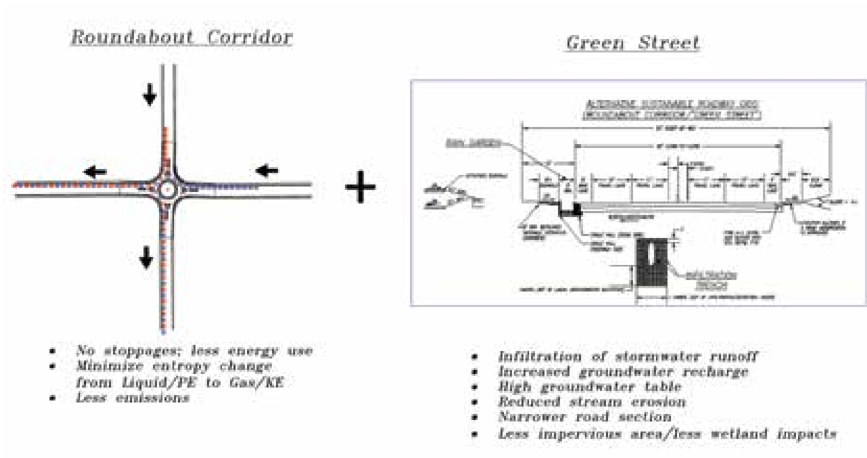


Table 1: One-mile roadway corridor; signalized intersections vs. roundabouts

	Signalized Intersections	Roundabout Corridor	% Reduction
TRANSPORTATION/ENERGY USE			
Capital cost	$10.4m/mile	$8.6/mile	17%
Annual fuel cost	$1.17m	$0.92m	21%
Travel time			21%
Intersection fatalities			89%
Intersection injuries			76%
STORMWATER/WATER CONSERVATION			
Annual runoff volume to streams	22.38 ac-ft	0 ac-ft	100%
Stream erosion			Reduced
Annual groundwater recharge	0 ac-ft	22.38 ac-ft	Improved
STREAM WATER QUALITY (ANNUAL POLLUTANT LOADINGS)			
Total suspended solids	452.7 lbs	0 lbs	100%
Total zinc	2.82 lbs	0 lbs	100%
Total copper	0.65 lbs	0 lbs	100%
Summer stream temperature			Reduced
AIR QUALITY/ENVIRONMENTAL			
Project impervious area	10.06 acres	9.09 acres	9%
Wetland impacts	1.89 acres	0 acres	100%
Total hydrocarbons			26%
Carbon monoxide			19%
Carbon dioxide	2102 tons	1660 tons	21%
Methane, nitrous oxide, HFC	105 tons	83 tons	21%

truly holistic and sustainable roadway grid system, as seen in these outcomes from a comparison between the two competing roadway grid alternatives:

The results show a reduction in energy use (here represented by annual fuel cost), confirming the roundabout corridor alternative as the more energy-efficient, more sustainable roadway grid.

As in previous examples, use of an entropy-based resource management strategy has led us to intervene early in a fundamental process to achieve our main objective as well as many additional benefits. There is something to please everyone. For capital budget hawks this is the cheapest, most cost-effective roadway infrastructure. For environmental advocates, there is carbon dioxide reduction and presumably some associated slowdown in global warming. Wetlands will benefit from improved groundwater recharge, and fish will benefit from deeper, cooler base flows in streams. And, for county citizens, there is a safe, fast, comfortable and inexpensive commute, surely what we are looking for in a good, sustainable roadway design.

Entropy based resource management and sustainability

The movement towards sustainability in general may also benefit from new applications of an entropy-based resource management strategy. For example, we may wish to develop more natural, multi-benefit storage systems for renewable energy. Recall from earlier discussion that natural systems work holistically across physical boundaries to create, store and use energy and resources efficiently. Could we mimic this holistic, multi-resource operation to convert kinetic wind energy into recoverable potential energy using some other resource? New techniques and adaptations of older methods come to mind, including linking up wind energy with off-peak pumped storage of captured stormwater runoff or with underground injection of compressed air.

The sustainable land use plan in an earlier article was created by optimizing the land use pattern for sustainable use of a single resource. Following an entropy-based resource management strategy to its logical conclusion, however, a fully sustainable land use plan would need to optimize all systems and resources necessary for life in the municipality. It would need to minimize the entropy of the entire urban area as an integrated system while supplying all the needs for a given population in a given geographic location.

Minimizing the entropy of a complex, interdependent, human-built system is a difficult quantitative exercise. However, as in the earlier example, we can opt to mimic a natural eco-system, say a Pacific Northwest forest, to provide clues as to how each individual discipline might contribute to a solution. Just as trees grow as high as possible, trapping as much of the sun's energy as possible and creating biomass, our buildings might tend to be taller and employ solar panels to supply the energy needed for the building and its inhabitants. Roof cisterns could be used to capture and store much of the annual rainfall at a high elevation, available for reuse. To minimize entropy changes in the transportation system, residential and work buildings would need to be close together, and the use of mass transit would be emphasized. And all traffic would need to use an orderly, sustainable roadway grid, with as many roundabout intersections as possible. For optimal water use, land use types would need to be arranged in a systematic way within the watershed as discussed in the earlier article.

Some of these measures are already being implemented, others may potentially be used in the future, and all are consistent with and can be conceived and developed using an entropy-based resource management strategy.

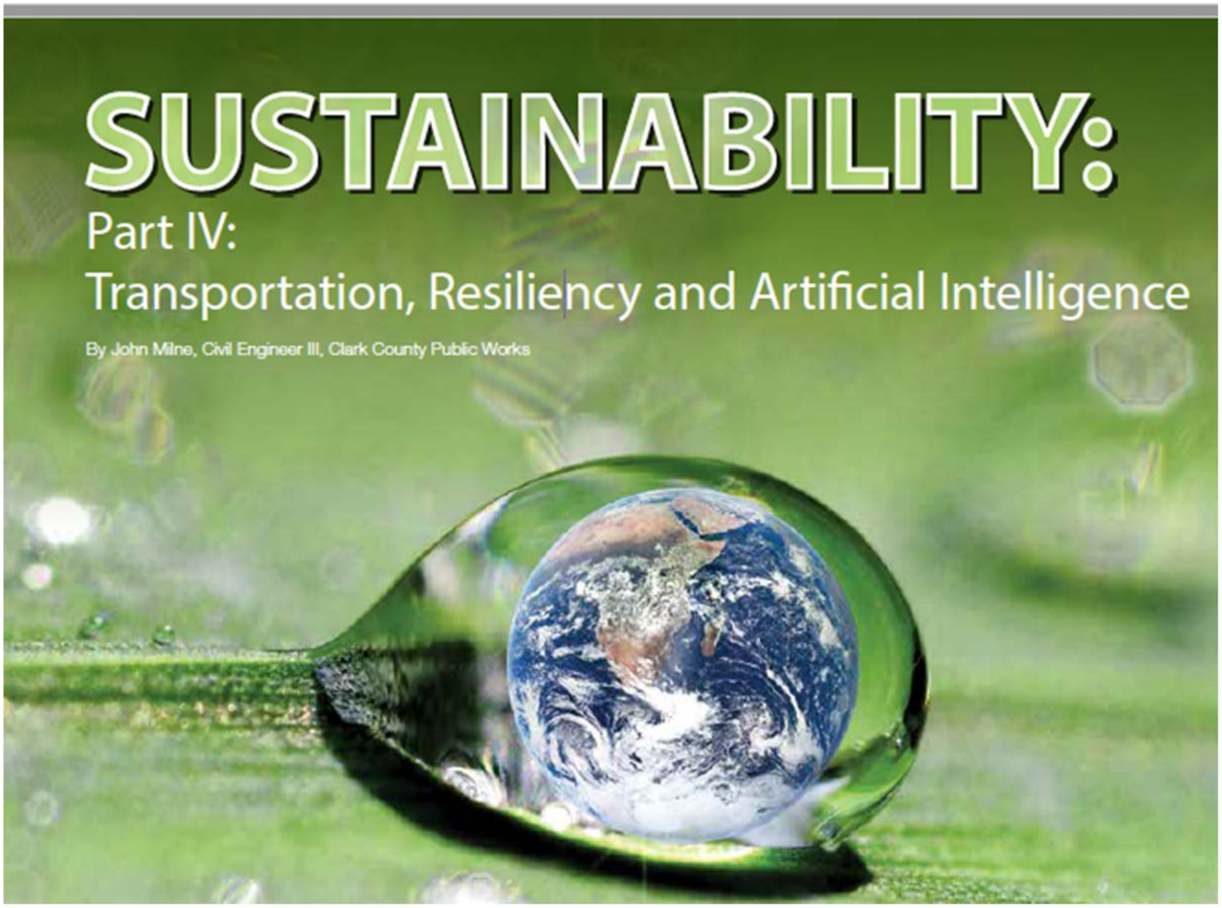
Conclusions

This three-part article has suggested how the use of entropy-based watershed management can help develop effective watershed rehabilitation strategies and also contribute to other areas of resource management and sustainability. Rather than focus on the many symptoms of watershed degradation, this strategy looks for the primary cause, looking directly at the second law of thermodynamics as the fundamental theory describing how natural resources are utilized and impacted and as the key to developing effective sustainability measures and programs.

Use of this principle has resulted in significant changes to the county's watershed management operations. In one respect, entropy-based watershed management can be thought of as "LID on a watershed scale." However, the strategy also emphasizes the need to minimize groundwater discharges and to preserve groundwater and surface water storage. The preservation and rehabilitation of headwater areas is similarly emphasized. Sub-basin retrofit plans facilitate the speedy rehabilitation of priority watershed areas, while sustainable land use plans may be effective in preventing watershed impacts in the first place.

A related entropy-based resource management strategy can potentially perform a similar function in promoting efficient energy use and the conservation and frugal use of other natural resources. The sustainable roadway grid example shows that effective interdisciplinary cooperation and coordination will be needed if we are to replicate the efficiency and holistic operation of natural systems. Order needs to be established not only at a molecular level, but in all our operations, programs, regulations and governmental structures, as we move towards a sustainable future.

As Ross the biologist says, "create negative entropy." Happiness will surely follow.



SUSTAINABILITY: "LIFE, LIBERTY AND THE PURSUIT OF NEGATIVE ENTROPY".

Part IV: Transportation, Resiliency and Artificial Intelligence

The entropy-based resource management approach was developed and first used in Clark County's stormwater management and watershed rehabilitation programs. More recent work has focused on the question "Can the entropy principles previously used for water management also be used for transportation?"

This article finds that not only can the organizing principle help shape sustainable transportation networks, but when used as guiding principle for resource management, it can help form alliances between multi-resource strategies to give us more sustainable cities. The article also shows that the entropy principle can be effective in meeting new challenges, including climate change and the introduction of autonomous vehicles and Artificial Intelligence technology into our transportation systems and infrastructure.

Introduction

Clark County's approach to stormwater management and watershed rehabilitation has focused on restoring the natural watershed hydrology using "entropy-based watershed management". A series of three 2013 articles introduced this organizing principle, and extended its application to cover additional resources (energy, air) and additional disciplines (transportation, land use planning).

This follow-up article completes a literature review of entropy-based transportation strategies and reaffirms the value of using the organizing principle to develop comprehensive, multi-resource sustainability strategies. The article goes on to suggest how its use can also be effective in meeting new challenges, including climate change and the introduction of autonomous vehicles and Artificial Intelligence technology into our transportation systems.

Entropy-based resource management: A recap

Entropy-based resource management is an organizing principle for developing strategies for the sustainable management of our natural resources and infrastructure. Its objective is to create and maintain order, i.e. to *create negative entropy*, in all our resources, at all times and in all places. The concept of creating and maintaining order is applied to all resource management activities, both physically (e.g. at the molecular level) and administratively, as in the development of a capital improvement program.

The organizing principle methodology uses simple, logical, qualitative and partly quantitative analyses to conceive and develop those sustainability strategies, in what can be thought of as a "back-to-basics" approach to sustainability. In earlier articles in this series, this approach was applied to the field of water resources and watershed management, for the most part. This Part IV now assesses whether the organizing principle can utilize recent traffic management research to advance sustainable transportation and land use planning strategies.

The first step, to complete a limited review of readily available entropy-based transportation strategies, is completed in the next section.

Review: Entropy-based analyses in transportation planning

A search of articles on entropy-based traffic management systems immediately yields several lines of inquiry. Curiously, both the "maximum entropy" analysis alluded to in the earlier articles and "minimum entropy" analyses can be found. Brief descriptions of several entropy-based transportation strategies along with some comment and discussion are provided below.

> *"Maximum Entropy and Utility in a Transportation System" (Mazumder et al., 1999)*
> This paper uses a maximum entropy methodology to optimize work trip-distribution in a transportation network, by maximizing travel options and traveller choices. The authors end by stating that "both entropy and utility can be adopted by skilful proponents to explain almost any form of transportation problem", confirming the value of entropy-based analysis in planning and designing efficient transportation systems.

> *"About the analogy between optimal transport and minimal entropy", (Gentil et al., 2016)*
> This paper takes a similar approach to that used for the "sustainable roadway grid" in the earlier articles to minimize the energy use (expressed as "entropic cost") within a transportation network. Interestingly, the article uses mathematical representations of Brownian motion to find a solution to the problem, reminiscent of the earlier articles' analogous references to liquid and gas states to determine the most ordered (i.e. least entropy) traffic flow through an intersection.

Taken together, these two articles show that seemingly contradictory approaches to solving a physical problem, a maximum entropy approach and a minimum entropy approach, can both help optimise transportation networks. The two articles also show the physical (thermodynamic) concept of entropy and the statistical concept of entropy used in information theory to be entirely compatible.

> *"Entropy in urban systems" (Cabral et al., 2013)*
> This paper applies entropy theory to detect, control and limit urban sprawl, a land use condition that is considered to be "inefficient resource allocation". A technique that eliminates or minimizes urban sprawl can clearly make a valuable contribution to the sustainable land use plan envisioned in earlier articles.
>
> *"Concept of transportation entropy and its application in traffic signal controls" (Zhou et al., 2013)*
> This paper introduces the concept of "transportation entropy" as a measure of disorder in a transportation system. Transportation entropy is made analogous to thermodynamic entropy by regarding the vehicles as energy outputs. Common mathematical techniques are then used to minimize the entropy, i.e. decrease the disorder within the transportation system, by optimizing the traffic signal controls.

The concept of order/disorder, depiction of vehicles as energy "packets" (my term), and the use of a four-intersection model as an illustrative example all bear similarities to the sustainable roadway grid concept proposed earlier in this series of articles. That proposal suggested the use of roundabout corridors as the most *orderly* traffic flow system, in a general sense.

At this juncture, we can see that combining the sustainable roadway grid concept with an optimized traffic signal control proposal will allow one vision, one "framework", of a sustainable transportation system to emerge. A transportation network that incorporates roundabout intersections wherever feasible, and uses entropy-optimized traffic controls at all other intersections, may show promise in developing sustainable roadway networks.

Clearly, link-ups can also be made between the entropy-based transportation analyses methods listed here, air quality/climate change considerations, and entropy-based water resource management strategies. Based on the literature review, the need for holistic, multi-objective, entropy-based resource management in the quest for sustainability, as suggested in the earlier articles, is confirmed.

The remainder of this article discusses additional aspects of using the organizing principle in a holistic "back-to-basics" approach to sustainability, which were brought forward by the literature review.

Development of new multi-resource strategies

When a new, multi-resource approach is first used, as opposed to a series of single-discipline analyses, it is logical that some simple new, holistic strategies must emerge. Combinations of practices that may potentially be very effective but have not been previously implemented would be discovered. For example the sustainable roadway grid proposal, formulated using the organizing principle, considered not only energy use but also air quality and water resources in arriving at an effective new multi-resource sustainability strategy.

To identify those new strategies, the organizing principle procedure first uses the simplest, most basic analysis methods. Those early analyses should be "as simple as possible, but no simpler". We begin with purely qualitative assessments and only slowly, after the use of qualitative methods has been exhausted, do we move on to partly-quantitative and, last of all, detailed quantitative analyses and modelling.

While these analyses might at first glance appear overly simplified when compared with some of the highly detailed computer modelling that is ongoing today, they do impose new discipline and rigor by insisting that the full array of natural resources is considered at all times. *Though simple, their value is confirmed if the resulting multi-resource strategy is found to be effective and there is no comparable strategy in current use.*

Note that the highly refined analytical procedures identified in the literature review were already fully developed. This current article merely suggests that they be combined with other entropy-based strategies to meet a wider range of sustainability needs. For example, any of the complex entropy-based transportation analyses listed earlier can easily become a sustainable roadway grid strategy simply by adding a green street roadway section. In this way the water resource would also be addressed (in addition to energy and air).

Mimicking natural systems

The earlier articles pointed to the value of mimicking natural systems. The papers reviewed here in Part IV confirmed the efficacy of this approach, using more elegant analogues coupled with more rigorous mathematical techniques. An environmental mimicry approach (noted as being "a bit hokey") was used in an earlier article to choose between a traffic signal and a roundabout as the default intersection for a sustainable roadway grid. In that example, a simple qualitative comparison of liquid vs. gas characteristics was used to select the roundabout as facilitating the more orderly (i.e. least entropy) traffic flow. Likewise, the article "About the analogy between optimal transport and minimal entropy" (Gentil et. al., 2016) depicted cars essentially as "energy packets" and then employed mathematical representations of Brownian motion to develop a highly efficient traffic signal control for an intersection. Both mimicry strategies have merit when integrated appropriately into the transportation network.

Note too that, while the mathematical techniques used in optimizing the traffic signal operation were very complex, the more straightforward comparison of liquid vs gas states put forward the roundabout, rather than the sophisticated entropy-based traffic signal operation, as the *default* intersection for a sustainable roadway grid. "As simple as possible, but no simpler", if well formulated and well considered, can trump highly sophisticated analysis.

These examples point to the efficacy and power of mimicking natural systems to find simple new solutions to what might initially appear to be complex, intractable problems in sustainability.

Compatible regulatory practices

The value of using the entropy-based resource management organizing principle can also be seen by considering two current regulatory practices. Both practices were developed independently of this organizing principle, but nonetheless apply its simple back-to basics approach, unknowingly but wisely, to achieve very effective management outcomes:

- On the transportation side, while optimizing travel choice can be complex, the widespread promotion and incentivization of multi-modal transportation can only produce good outcomes when included as part of a comprehensive transportation strategy.

- On the water resources side, the widespread use of Low Impact Development BMPs can provide great benefits for groundwater recharge (although groundwater *discharges* would also receive due consideration in a comprehensive entropy-based strategy).

So, "Complete Streets" and "Green Streets" are both good. However, an entropy-based variant, a "Green Complete Street" (now addressing water, energy and air), may be still better. The sustainable roadway grid proposed in earlier articles might be thought of as an example of a Green Complete Street.

Resilience to Climate Change

While it is important that work on sustainability continues apace, attention more recently has shifted to the pressing need for resiliency measures to cope with climate change. In reality, sustainability and resiliency may be two sides of the same coin, and use of the entropy-based resource management organizing principle can help develop solutions that will work for both.

For example:

- Electric and driverless vehicles will reduce both fossil fuel use (energy; sustainability) and emissions (greenhouse gases; resiliency).

- LID BMPs, intended to recharge groundwater supplies (sustainability), will work equally well to limit the effects of drought and to reduce flood damage (resiliency needs).

As scarcities of various kinds develop as outcomes of climate change, the need for sound physics coupled with powerful mathematical techniques to find optimised solutions will grow. Based on the information covered in this series of articles, the entropy-based resource management organizing principle can provide a useful and effective framework for developing those solutions.

Artificial Intelligence and Autonomous Vehicles

The introduction of driverless cars will create a still greater need for optimized traffic management systems. With human-made travel choices being supplanted by computer software, the need for sound, physically-based algorithms that can fully optimize "electronic decision-making" will increase. Artificial Intelligence innovations in vehicles and in the transportation infrastructure will incorporate those algorithms. Based on the information found in the literature review, it appears likely that entropy-based traffic management methods and their associated mathematical procedures will play an important role in developing the transportation systems and AI software that will be needed.

Of course, a rigorous, comprehensive application of the organizing principle would then require that all traffic systems employ the use of green streets in-between intersections, to give us a truly sustainable roadway network. Entropy-based strategies covering energy, air and water, the building blocks for the city's population, will now have been integrated and will work together to produce an outcome that is truly "more than the sum of its parts". We now will have a truly holistic and sustainable infrastructure system.

Entropy based resource management and "The Sustainable City"

This series of articles has introduced and explored the use of an entropy based resource management organizing principle as a means of developing sustainability strategies, chiefly in the area of water resources. This Part IV article has demonstrated that the organizing principle can be equally, if not more, effective when applied to transportation and related land use planning challenges.

Part IV also showed that a well-thought out sustainability approach can effectively address challenges arising from climate change. Entropy-based strategies and their supporting mathematical techniques can also help provide the algorithms needed for Artificial Intelligence to further improve efficiencies within the transportation system, and help effectuate the successful integration of driverless cars and autonomous vehicles into our cities and societies. All can be accomplished in a holistic manner, with each individual strategy supporting all others in a "virtuous cycle" or "positive feedback loop".

By way of illustration, an Entropy-based Resource Management Plan for a "Sustainable *(and resilient)* City", broadly targeted at the water, energy and air resources needed for life in the city, might include the following:

Energy
Employ entropy-based transportation strategies to minimize the work needed for home-to-work travel and all other trips. Develop energy-efficient electric vehicles to perform that work as efficiently as possible.

Supporting strategies are:

- Multi-modal transportation systems.

- Replace fossil-fuel energy with more available and efficient (and less harmful) renewable energy sources.

Implementation measures can include a sustainable land use plan that merges econometric analyses with entropy-based transportation systems. Ongoing operations would rely heavily on the use of AI and “smart city” technology.

Additional compatible measures include Complete Streets, a sustainable roadway grid, driverless cars and autonomous vehicles, “First Mile” transportation choices, “20-Minute Neighbourhoods”, roundabouts, vehicle-activated traffic signals, entropy-based traffic signal optimization, entropy based limits on urban sprawl.

Supporting private initiatives include the increased use of solar energy, wind energy linked to pumped storage or underground injection of compressed air, turbines inside gravity water supply lines, artificial photosynthesis for fuel.

Water
Emphasize the establishment and maintenance of high groundwater elevations in all places at all times.

This will maximize retention of the annual rainfall supply within the watershed. That in turn will maximize the availability and residence time of water throughout the watershed.

Supporting strategies are:

- Infiltration-retention-detention hierarchy for disposal of stormwater runoff.
- Flood flow capture and aquifer replenishment.
- Headwater wetland restoration projects.
- Trench dams in pipeline and utility trenches.
- Runoff flow control.

Implementation can be achieved through the inclusion of an envirometric overlay within a sustainable land use planning process. In the absence of a detailed land use plan, “pump up the groundwater then plant everywhere” can serve as a reasonable envirometric *game plan* for a community faced with sustainability and resiliency challenges.

Additional compatible measures include “One Water” strategies, Low Impact Development BMPs, Green Streets.

Air
Increase photosynthesis.

Reduce greenhouse gas emissions.

Supporting strategies are:

- Entropy-based water resource management strategies will increase the availability of water to encourage photosynthesis and vegetation growth, energy production and removal of carbon from the atmosphere.
- Entropy-based transportation strategies will reduce greenhouse gases and improve air quality.

Implementation can be achieved though use of a sustainable land use plan developed using econometric analyses integrated with entropy-based transportation and water resource management strategies.

Additional compatible measures include reforestation, electric vehicles.

Conclusions
This concluding article in the series has completed a brief literature review of entropy-based traffic analysis methods to determine whether they can be linked-up with compatible entropy-based watershed management techniques to form holistic, multi-resource sustainability strategies.

The results of the review reaffirm the value of entropy-based resource management as an effective “back-to-basics” organizing principle for developing sustainability strategies.

The following general conclusions are also noted:

1. Entropy-based resource management techniques, properly formulated, will

also serve as effective resiliency measures against climate change.

2. Entropy-based transportation strategies can help effectuate the incorporation of Artificial Intelligence technology, driverless cars and autonomous vehicles into public infrastructure and the transportation system.

3. Multi-resource strategies and multi-discipline teamwork are both needed to produce the "whole is more than the sum of its parts" efficiencies of a truly holistic sustainability program.

Ensuring economic and environmental sustainability into the future can be achieved by a diverse, multi-discipline team using the entropy-based resource management organizing principle. With sustainability a continuing need, with resiliency to climate change becoming more urgent, and with the widespread incorporation of Artificial Intelligence into our infrastructure systems imminent, it's time to get started.