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# Emergy and Water Policy

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**Abstract:** The value of water means different things to different people. For example, consumers care about how much their water bill is each month. However, for different levels of government, the value takes on dissimilar meanings depending on the governmental entity (local, regional, or country). Incorporating costs of retrieval and processing are a key to good water policy. Location and timing are also important factors impacting the valuation of water. For instance, in times of scarcity the value goes up. Therefore, a mechanism needs to be put in place that can help improve the water policy process at all levels and under all conditions. Outlined within this review is the importance of incorporating emergy into that analysis, since it helps with the decision making process by integrating the variables from the entire water process including retrieval, purification, and distribution.

**Keyword:** Emergy, Water Costs, Water Policy.

## 1. BACKGROUND

What is the true cost of water and how should this impact its price? This is a policy question that has long-term implications since access to unpolluted fresh water with sufficient supply and at an affordable price is essential for all people. The sustainability of freshwater supplies is a major issue around the world, and increased climate change extremes are exacerbating the risks. The amount of energy used to procure, treat, transport, and supply potable water can be factored into its cost, particularly in light of the energy transition away from fossil fuels. Emergy related variables provide a means to rank water extractions, purification, and distribution systems, all of which affect the price charged for water. Thus, emergy related calculations adds additional variables that should be incorporated into long-term water policy decisions.[1] Emergy variables, as used in this review, are measures that capture the different energy sources required to produce potable water. Inputs include not only contributions from the human capital, energy, fuels, goods, and materials but those typically classified as “free” coming from nature (such as sun, wind, rain, tide, and geologic cycles). Emergy analysis is therefore a tool that can complement tra ditional cost-benefit analysis to make more integrated resource management decisions.[2]

Water, water everywhere, but not a drop to drink.[3] Although it is not that bad, yet, drinkable water is becoming scarcer as it is being wasted at a faster rate than ever before. Past emergy studies have focused on different aspects of water such as chemical potential energy, geopotential energy, valuation of the nutrients, suspended solids and dissolved solids in the water, and the use of water to treat waste products. For instance, Odum et al. (1987b) uses emergy-based dollar valuations per cubic meter of water (Em\$/m$^3$) to establish a baseline for setting irrigation policy within Texas based on chemical potential energy. The valuation for rain, river, and groundwater were relatively low at 0.035, 0.091, and 0.250 Em\$/m$^3$ respectively. But as the water was further refined for agricultural and municipal drinking settings, the valuations increased to 0.44 and 1.16 Em\$/m$^3$ respectively. These were 11 and 1.5 times greater than the corresponding market values, indicating a mismatch between valuations and pricing. From the geopotential energy viewpoint, Romitelli (1997) valued river water in the Ribeira de Iguape River Basin between Curitiba and Sao Paulo in Brazil using both dollar (Em\$/m$^3$) and emergy (Em/m$^3$) based valuations. Romitelli documents the increasing geopotential valuation as the water flows downstream. At the Eta sub-basin upstream the value is 1.9 E11 sej/m$^3$ (0.023 Em\$/m$^3$) versus the downstream value at the Betari sub-basin of 2.2 E12 sej/m$^3$ (0.26 Em\$/m$^3$). Thus, water extraction at different locations along the river should have different prices set if based on the underlying cost factors.

Brandt-Williams (1999) offers an example of a nutrient valuation assessment. Evaluating the emergy of water in Newman’s Lake and Lake Weir in central Florida, phosphorous accounted for approximately 23% and 4.4% of the value in

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[1] See Odem (1996), Odum, et al., (1987a), Odum, et al., (1987b), Odum (2000) for some of the pioneering work within the emergy field. See Brown et al., (2016) for a synthesis of later research and controversies with emergy.

[2] For an example of emergy variables being used in water policy see Andres A. Buenfil, Emergy Evaluation of Water Supply Alternatives for Windhoek, Namibia in IR-00-031 / May 2000 Population-Development-Environment in Namibia http://pure.iiasa.ac.at/id/eprint/6214/1/IR-00-031.pdf

[3] Paraphrased from *Water, water, everywhere, And all the boards did shrink; Water, water, everywhere, Nor any drop to drink. From* – “The Rime of the Ancient Mariner” by Samuel Taylor Coleridge.

Newman's Lake (3.44 E11 sej/m$^3$ or 0.22 Em\$/m$^3$) and Lake Weir (9.75 E10 sej/m$^3$ or 0.063 Em\$/m$^3$) respectively. Thus, nutrients could be an added factor into water cost calculations. In a water treatment example, Nelson (1998) calculated the emergy value of highly treated wastewater effluent in Gainesville Florida as 2.32 E14 sej/m$^3$ or 170.1 Em\$/m$^3$. The high valuation is attributed to the underlying raw sewage, a side product of the treatment facility which should be used to lower the cost to the consumer. But dollar and emergy volume ratios should not be used in isolation. These valuations need to be used within an integrated decision making process.

Water although a basic commodity, is a necessary ingredient for life. So, how can water be accurately valued? In addition to quantity, we also need to consider its retrieval, purification, and delivery systems since the cost of water is locale dependent. For instance, the average cost of water in the U.S. based on 50, 100, and 150 gallons per month usage from 30 representative cities was $35.49, $70.39, and $112.84 respectively in 2018.[4] These costs ranged from the minimums for 150, 100, and 50 gallons per month at $44.52, $29.68 (in Memphis, TN) and $12.22 (in Phoenix, NV) to the maximums of $284.10, $153.78 (in Santa Fe, NM), and $71.79 (San Francisco, CA). Note that the lowest cost ($0.24 per gallon) does not seem to cover the true cost of retrieval, purification, and transporting the water to the end user. Interesting, less than half of the selected cities sited charged lower per gallon costs for the minimal usage amounts to encourage conservation. See Table **1** for the costs at the three usage levels for these 30 select cities.[5] A survey of cities in developed countries also indicates that water charges may not reflect its true cost. Table **2** shows the 14 cities offering the lowest average prices for water. For example, in Milan, Italy the cost for 200 cubic meters of water was only $53.44, which is approximately $0.20 per gallon. Since water is a necessary component for life, there is justification for subsidizing its true cost in the potable water marketplace. But emergy components can help reinforce policy decisions on where and how much this subsidy should be.

**Table 1. Monthly Water Cost for Representative U.S. Cities.**

| City | 150 gallons (cost/gal) | 100 gallons (cost/gal) | 50 gallons (cost/gal) | Conservation Discount |
|---|---|---|---|---|
| Atlanta, GA | $141.20 ($0.94) | $91.92 ($0.92) | $42.64 ($0.85) | Yes |
| Austin, TX | $197.37 ($1.32) | $119.61 ($1.20) | $37.45 ($0.75) | Yes |
| Baltimore, MD | $79.26 ($0.53) | $59.39 ($0.59) | $39.51 ($0.79) | No |
| Boston, MA | $131.00 ($0.87) | $86.00 ($0.86) | $42.83 ($0.86) | Yes |
| Charlotte, SC | $130.63 ($0.87) | $59.35 ($0.59) | $21.67 ($0.43) | Yes |
| Chicago, IL | $69.84 ($0.47) | $46.56($0.47) | $23.28 ($0.47) | Constant |
| Columbus, OH | $83.54 ($0.56) | $57.86 ($0.58) | $32.18 ($0.64) | No |
| Dallas, TX | $96.30 ($0.64) | $51.45 ($0.51) | $21.69 ($0.43) | Yes |
| Denver, CO | $62.10 ($0.41) | $42.87 ($0.43) | $29.13 ($0.58) | No |
| Detroit, MI | $64.04 ($0.43) | $45.04 ($0.45) | $26.03 ($0.52) | No |
| Fort Worth, TX | $83.20 ($0.55) | $54.52 ($0.55) | $30.76 ($0.62) | No |
| Fresno, CA | $48.08 ($0.32) | $36.02 ($0.36) | $23.96 ($0.48) | No |
| Houston, TX | $118.94 ($0.79) | $66.38 ($0.66) | $34.46 ($0.69) | Yes/No |
| Indianapolis, IN | $96.85 ($0.65) | $67.46 ($0.67) | $38.07 ($0.76) | No |
| Jacksonville, FL | $63.49 ($0.42) | $43.30($0.43) | $23.11 ($0.46) | No |
| Las Vegas, NV | $75.82 ($0.51) | $53.20 ($0.53) | $34.92 ($0.70) | No |
| Los Angeles, CA | $182.71 ($1.22) | $109.59 ($1.10) | $47.49 ($0.95) | Yes |
| Memphis, TN | $44.52 ($0.30) | $29.68($0.30) | $14.84 ($0.30) | Constant |
| Milwaukee, WI | $58.99 ($0.39) | $42.36 ($0.42) | $25.71 ($0.51) | No |
| New York, NY | $91.44 ($0.61) | $60.96 ($0.61) | $30.48 ($0.61) | Constant |
| Philadelphia, PA | $107.84 ($0.72) | $75.54 ($0.76) | $41.07 ($0.82) | No |
| Phoenix, NV | $71.58 ($0.48) | $40.54 ($0.41) | $12.22 ($0.24) | Yes |
| Salt Lake City, UT | $44.63 ($0.30) | $31.99 ($0.32) | $19.91 ($0.40) | No |
| San Antonio, TX | $111.77 ($0.75) | $66.69 ($0.67) | $30.72 ($0.61) | Yes |
| San Diego, CA | $198.83 ($1.33) | $117.96 ($1.18) | $65.38 ($1.31) | Yes/No |
| San Francisco, CA | $209.71 ($1.40) | $140.75 ($1.41) | $71.79 ($1.44) | No |
| San Jose, CA | $112.62 ($0.75) | $83.98 ($0.84) | $55.34 ($1.11) | No |
| Santa Fe, NM | $284.10 ($1.89) | $153.78 ($1.54) | $54.78 ($1.10) | Yes |
| Seattle, WA | $160.34 ($1.07) | $104.53 ($1.05) | $59.30 ($1.19) | Yes/No |
| Tucson, AZ | $140.49 ($0.94) | $72.41 ($0.72) | $35.20 ($0.70) | Yes |

Source: Circle of Blue—where water speaks https://www.circleofblue.org/2016/world/price-water-2016-5-percent-30-major-u-s-cities-48-percent-increase-since-2010-2/

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[4] Data was obtained from a 2017 waterstatistics.iwa-network.org survey in which 198 cities responded.

[5] See circle of blue https://www.circleofblue.org/2016/world/price-water-2016-5-percent-30-major-u-s-cities-48-percent-increase-since-2010-2/

**Table 2. Lowest Average Water Prices by Representative Cities.**

| City, Country | Cost/200 $m^3$ | Cost/gal |
|---|---|---|
| Milan, Italy | $53.44 | $0.2023 |
| Yerevan, Armenia | $63.35 | $0.2398 |
| Taipei, Thailand | $83.41 | $0.3157 |
| Guangzhou, China | $91.36 | $0.3458 |
| Kaohsiung, Taiwan | $95.49 | $0.3615 |
| Daejeon, South Korea | $99.33 | $0.3760 |
| Shanghai, China | $101.51 | $0.3843 |
| Moscow, Russia | $106.71 | $0.4039 |
| Seoul, South Korea | $107.24 | $0.4059 |
| Hong Kong | $113.96 | $0.4314 |
| Guadalajara, Mexico | $114.89 | $0.4349 |
| Gwangju, South Korea | $116.67 | $0.4416 |
| Monterrey, Mexico | $122.01 | $0.4619 |
| Shenzhen, China | $123.35 | $0.4669 |
| Beijing, China | $125.20 | $0.4739 |
| Incheon, South Korea | $125.87 | $0.4765 |

Source: statista https://www.statista.com/statistics/478888/leading-cities-based-on-lowest-freshwater-prices/

## 2. WATER VALUATION USING EMERGY

Emergy is the available energy of one kind previously required directly and indirectly to make a product or service. The unit of measurement for solar emergy, the key focus of most emergy studies, is solar emjoules (sej). These quantitative emergy components can be useful in comparing various water options such as the comparison of various retrieval and purification mechanisms. Some of the earliest contributors of the emergy concept focused on three key factors: chemical potential energy,[6] geopotential energy,[7] and nutrients, suspended solids and dissolved solids present in water.8 The variability of the sample of emergy water valuations, summarized in Table **3**, help document that the valuation of water is locale dependent.

**Table 3. Sample Water Values of U.S. Studies.**

| Water type and location | Em\$/$m^3$ | Source |
|---|---|---|
| **Rain** | | |
| North Carolina (a) | 0.006 | Tilley 1999 |
| U.S. (a) | 0.028 | Odum 1996 |
| U.S. (b) | 0.032 | Odum 1996 |
| Texas (b) | 0.035 | Odem, et al., 1978b |
| **River & River Basin Waters** | | |
| Mississippi River (c) | 0.002 | Odem, et al., 1987a |
| Texas (b) | 0.091 | Odem, et al., 1987b |
| Coweeta River Basin, North Carolina (a) | 0.290 | Romitelli 1997 |
| **Lake Water** | | |
| Lake Weir, Florida (b) | 0.063 | Brandt-Williams 1999 |
| Martin County, Florida (b) | 0.150 | Engel et al., 1995 |
| Newman's Lake, Florida (b) | 0.220 | Brandt-Williams 1999 |
| **Groundwater** | | |
| U.S. (b) | 0.070 | Odum 1996 |
| Texas (b) | 0.250 | Odum et al., 1987b |
| North Carolina (b) | 0.620 | Tilley, 1999 |

Note: (a) Geopotential energy of water; (b) chemical potential of water; (c) sediment present in water.

Emergy, as a measurement, is not without controversy. Brown et al., (2016) outlines the need for a common emergy baseline. The original baseline established by Odum (1996), was modified by Chem (2005) to include cosmic emergy. Raugei (2013) expanded the baseline to include sunlight and tidal momentum, as well as, geothermal heat. Brown and Ulgiati (2016) also expand the baseline calculations to include solar, tidal, and geothermal. Key to their analysis was that the solar base, the most frequently used emergy form, remains unchanged from Odum (2000).

## 3. SELECT STUDIES HIGHLIGHTING EMERGY BASED WATER DECISIONS

Several key studies are highlighted to show how emergy can be a useful tool in the water valuation and policy process. The true value of water is dependent upon its hierarchy within the water cycle, i.e., how much it has been processed. For instance, sea water has low emergy value since it unprocessed. As evaporated seawater converges into clouds which precipitates into rain, it gains additional emergy value as it is being refined. Water collected from rivers, lakes, and groundwater to be further refined through treatment plants should also show an increase in emergy value. Transformities and emergy-based dollar valuations per cubic meter of water (Em\$/$m^3$) are useful for quantifying these values.

### 3.1. Treatment Options—Florida, U.S.A.

Buenfil (2001) ranks seven public water supply utilities in Florida based on efficiencies. Figure 1 summarizes a generalized economic production system which is the foundation

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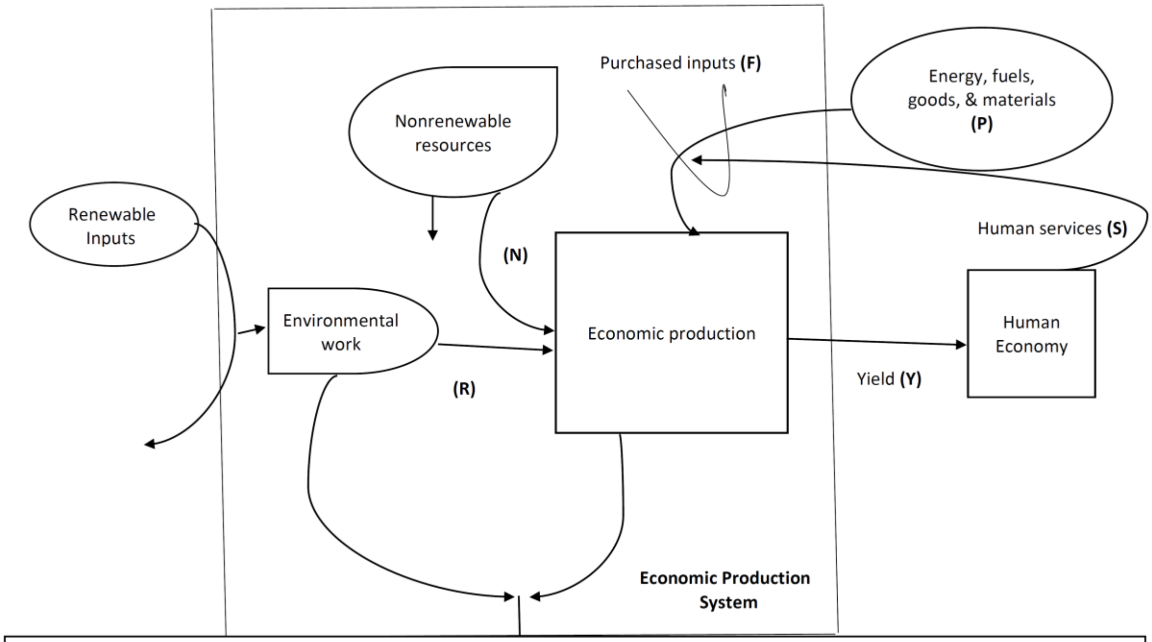
[6] The chemical potential of water can be defined as the free energy per mole of water. That is, the potential for a substance to react or move. Chemical potential depends on the mean free energy of water and the concentration of water molecules (which chemically is referred to as the mole fraction). Thus, pure water will have a higher chemical potential than will a solution.

[7] Geopotential of water is the difference between the potential energy of water at a given altitude and the potential energy of water at sea level. Odum's (1996) estimate of the geopotential energy of rain falling within the U.S. at 0.028 Em\$/$m^3$.

[8] Odum et al., (1987a) evaluating Mississippi River Basin sediments placed their valuation at 0.003 Em\$/$m^3$. Thus, the type of sentiment within water generate different values.

for the emergy network. Building upon this flowchart, the appendix summaries the most common variables used within the emergy decision process. Highlighted within Buenfil's study are several of the key variables utilized in the valuation process.

1) **Emergy investment ratio (EIR)**—a measure of the intensity of the production process. EIR is computed as the quotient of the purchased inputs (F) and the free renewable and nonrenewable emergy inputs (R+N). The lower the EIR, the more efficient the system.
2) **Emergy yield ratio (EYR)**—the quotient of the emergy of the output (Y) and the emergy of the purchased inputs (F). Inputs can be separated into two classifications: renewables (inputs obtained free from nature: R) and purchased/operational (inputs with a cost factor: F = P + S). Purchased inputs (P) include energy, fuels, goods, and materials. Operational inputs included the cost of human services (S). The higher the EYR, the greater the return on the investment.
3) **Percent renewable emergy (%Renew)**—calculated by dividing renewable emergy by the emergy yield times 100 (R/Y*100). The larger the %Renew, the more sustainable the production process long term.
4) **Emergy-dollars per volume (Em\$/m$^3$)**—represents the cost of producing one cubic meter of water. Emergy/m$^3$ (Em/m$^3$), the amount of emergy necessary to produce a cubic meter of water, is a precursor to this fourth variable. Em\$/m$^3$ is both time and currency dependent, i.e., the value for any specific time period is calculated by taking emergy per volume (sej/m$^3$) of water by the emergy-per-dollar ratio (sej/\$) calculated at that particular time period. The currency used is country or area specific dependent upon where the water is produced. A lower Em\$/m3 is indicative of a lower cost structure.
5) **Transformity** (sej/J) is calculated by dividing the emergy yield (Y) by the J. The lower the transformity, the greater the efficiency of the production process. Note that emergy yield (Y) is the sum of both renewable (R) and nonrenewable (N) resources plus purchased inputs F (i.e., Y = R + N + F).



Emergy Indices: Purchased inputs (F) = P+S; Emergy Yield (Y) = R+N+F; Emergy Investment Ratio (EIR) = F/(R+N);
Emergy Yield Ratio (EYR) = Y/F; % Renewable = R/Y*100; Transformity of Y = (emergy of Y)/(energy of Y); and
Emergy Benefit to Purchaser (EBP) = (emergy of Y)/(emergy of \$ paid for Y); Em\$/m3 = (Y/m3 of Y)/(sej/\$)

**Fig. (1).** Emergy Factors.

The seven supply alternatives evaluated include three treatment plants (West Palm Beach, Tampa, and Gainesville), Tampa Bay conservation program, reverse osmosis plant at Dunedin, Tampa Bay desalination plant, and an aqueduct in the Florida Keys. A summary of the results are shown in Table **4**. The first variable is the emergy investment ratio. EIR measures the amount of resources employed within the treatment process. Thus, the lower the EIR, the greater the benefit to the economy. The Gainesville treatment plant shows the best outcome with an EIR of 0.78. The reverse osmosis at Tampa Bay (EIR 32.39) shows the least efficient system. The second variable is the emergy yield ratio. A higher EYR indicates that the underlying resource helps to stimulate the economy at a lower cost. Thus, the conservation program undertaken within the Tampa Bay area with the highest EYR at 2.57 indicates it has the largest stimulus factor of the supply alternatives studied. This is followed by the Gainesville treatment plant with an EYR of 2.27. Both alternatives contribute net emergy to the economy, and thus help the promotion of development and high standards of living. The third variable is the percentage of renewable emergy. %Renew gives an indication of the sustainability of the process in the long run. Therefore, the higher the %Renew, the better. Again, the Gainesville treatment plant tops the list of alternatives.

The fourth variable, the emergy-based dollar valuations per cubic meter of water (Em\$/m$^3$), is a cost indicator. The lower the valuation, the more efficient the water is being produced. The West Palm Beach surface water treatment plant which receives its water supply from lakes shows the lowest cost due to the lower treatment required for purification. The cost ratios offer support for the need to protect our watersheds. The higher the quality and quantity of water inputs, the lower the final cost of the water distributed. The fifth variable, tranformity (Tr), is a measure of the efficiency of the production process. The lower the tranformity, the more efficient the process. Thus, the West Palm Beach faculty again is gains the topped rank. An additional variable, the emergy benefit to the purchaser (EBP), could also be beneficial to policy formation. EBP is defined as the emergy of the product divided by the buying power of the money paid for the product in terms of emergy. As EBP increases, more free wealth is transferred to the consumer, which should promote a higher standard of living. Thus, the high EBP of the conservation program in the Tampa Bay area indicates a high benefit for society. It helps conserve water and protect the environment, both at a low cost to society. The high EBP generated by the Gainesville treatment plant should be used as an argument to encourage municipal water use and forgo bottled water and other alternatives.

Unfortunately, the variables used do not always tally consistent rankings. Therefore, if the major concern is appropriate use of resources and long run viability, then EIR, EYR, and the %Renew should have the most relevance for policy implications. But, if the emphasis is on efficiency and the least emergy cost, then transformilities and emergy costs (Em\$/m$^3$) are the more appropriate variables. Although the alternatives treatment options can be ranked, it still may not be possible to introduce a superior treatment process into another locale due to exterminating circumstances beyond the locales control.

**Table 4. Summary Emergy Indices and Ratios.**

| | | **Treatment Plant** | | | **Conservation** | **Reverse Omosis** | **Desalination** | **Aqueduct** |
|---|---|---|---|---|---|---|---|---|
| **Index** | **Sign** | **W Palm Beach** | **Tampa** | **Gainesville** | **Tampa Bay** | **Dunedin** | **Tampa Bay** | **FL Keys** |
| Treatment | | Coagulation & settling | Coagulation & settling | Lime softening | Conservation | Reverse osmosis | Reverse osmosis | Lime softening |
| Source | | Surface: lakes | Surface: rivers | Groundwater: aquifer | Potable water saved | Brackish: groundwater | Seawater | Groundwater |
| EIR | ↓ | 1.43 | 3.10 | **0.78** | 2.61 | 1.14 | 32.39 | 6.74 |
| EYR | ↑ | 1.70 | 1.32 | 2.27 | **2.57** | 1.88 | 1.03 | 1.15 |
| %Renew | ↑ | 41.20 | 24.39 | **56.00** | 14.90 | 46.70 | 3.00 | 12.90 |
| Em\$/m$^3$ | ↓ | **0.75** | 1.01 | 1.60 | 1.66 | 2.06 | 2.48 | 2.96 |
| Transformity | ↓ | **1.39E+05** | 1.87E+05 | 2.95E+05 | 3.06E+05 | 3.80E+05 | 4.57E+05 | 5.45E+05 |
| Em/m$^3$ | ↑ | 6.85E+11 | 9.23E+11 | 1.46E+12 | 1.51E+12 | 1.88E+12 | 2.26E+12 | **2.69E+12** |
| EBP | ↑ | 2.46 | 2.53 | 4.37 | **12.07** | 3.35 | 4.91 | 1.71 |

Note: EIR—Emergy Investment Ratio = (P+S)/(N+R); EYR—Emergy Yield Ratio = Y/(P+S);
%Renew--%Renewable emergy = 100 * (R/Y); EBP—Emergy Benefit to the Purchaser in 1999 dollars = Em\$/\$;
Em-dollar value of potable water per m$^3$ = Em\$/m$^3$; Transformity of potable water = sej/J; and
Emergy per m$^3$ of potable water Em/m$^3$ = sej/m$^3$

**Bold** indicates best in class.

## 3.2. Groundwater Valuation—Beijing, China

Our second study, the analysis of groundwater in Beijing, China by Wang and He (2015) highlights the vetting of government initiatives to determine which were successful and should be continued. Their analysis relies on emergy (sej) and a valuation of emergy (i.e., emergy per the gross domestic product—GDP comparison price). Since the valuation is undertaken using the local currency, renmindi (¥), versus U.S. dollar, the valuation is emergy/GDP¥ (sej/¥) versus emergy/GDP\$ (sej/\$). GDP comparison prices are locale dependent. They could be defined for a city, state, region, or nation. For instance equation (1), the emergy per renmindi ratio (Em¥) is defined as emergy generated from the component under study divided by the base valuation of the underlying system. Thus, Em¥ defines the energy and the emergy network of water within an ecological-economic system.

$$Em¥\ (sej/¥) = \frac{Em_U}{GDP\ Comparision\ Price} = \frac{Em_R + Em_N + Em_F - Em_{EX}}{GDP\ Comparision\ Price} \qquad (1)$$

Where EmU, the total emergy, used is composed of EmR (renewable emergy), EmN (nonrenewable emergy), EmF (feedback emergy), and EmEX (export emergy). Emergy per dollar (Em$) is also reported, but is redundant since the rank order is the same. Valuations in renminbi for the years 2008 through 2012 are: 6.76, 6.49, 7.26, 8.11, and 9.51 (1011 sej/¥).9 This shows an increasing valuation for water over time, reflecting its increased scarcity as the population increases. Thus, water policy should factor scarcity into the prices charged as a way to encourage conservation. See Table 5 (Panel A) for the supporting values for the emergy components EmR, EmN, EmF, EmEX, and EmU, which shows an increasing dependency on the nonrenewable sector.

Equation (2) defines the groundwater resource (GWCR) network for three subsystems: industrial (subsystem I), agricultural (subsystem A), and residential (subsystem R).

$$GWCR_{Subsystem_x} = \frac{Emergy\ of\ Subsystem_x}{All\ Emergy\ Input\ within\ Subsystem_x} \quad (2)$$

The groundwater resources averaged over the years 2008 through 2012 are 0.944%, 4.38%, and 3.81% for GWCRI, GWCRA, and GWCRR respectively. See Table **5** (Panel B) for the values of the individual years within each of the three subsystems: industrial, agricultural, and residential. The results show a decline in the latter years for both the industrial and residential sectors. The declining values indicate that water policy needs to focus on reducing water usage or finding additional sources of water as the population increases. The agricultural sector is flat.

**Table 5. Summary of Emergy Factor within the Beijing Water System**

| **Panel A: Emergy index** (unit: $10^{20}$ sej) | | | | | | |
|---|---|---|---|---|---|---|
| | **2008** | **2009** | **2010** | **2011** | **2012** | **Average** |
| $Em_R$ | 459 | 324 | 378 | 398 | 509 | 414 |
| $+Em_N$ | 1,202 | 1,287 | 1,319 | 1,107 | 977 | 1,178 |
| $+Em_F$ | 8,139 | 8,619 | 11,372 | 14,863 | 17,509 | 12,100 |
| $-Em_{EX}$ | 3,919 | 3,998 | 5,529 | 7,296 | 8,367 | 5,822 |
| $= Em_U$ | 5,881 | 6,232 | 7,540 | 9,072 | 10,627 | 7,870 |
| **Em¥ (sej/¥)** | **6.76** | **6.49** | **7.26** | **8.11** | **9.51** | **7.63** |
| **Panel B: Contribution Rate of Water Resources** (unit: %) | | | | | | |
| Category | 2008 | 2009 | 2010 | 2011 | 2012 | Average |
| $GWCR_I$ | 1.65 | 0.86 | 0.77 | 0.73 | 0.71 | 0.94 |
| $GWCR_A$ | 4.35 | 3.81 | 4.34 | 4.86 | 4.52 | 4.38 |
| $GWCR_R$ | 4.42 | 4.10 | 3.91 | 3.38 | 3.25 | 3.81 |

| **Panel C: Transformity** (unit: $10^{13}$ sej/m$^3$) | | | |
|---|---|---|---|
| | Total | From Surface Water | From Ground Water |
| $Tr_{NW}$ | 3.34 | 3.29 | 3.41 |
| $Tr_{EW}$ | 0.317 | 0.23 | 0.35 |
| $Tr_{RE}$ | 1.19 | | |

| **Panel D: Summary of Beijing Groundwater Value** | | | | | | |
|---|---|---|---|---|---|---|
| **For Industry** | | | | | | |
| | 2008 | 2009 | 2010 | 2011 | 2012 | Average |
| Emergy ($10^{20}$ sej) | 50.70 | 44.36 | 52.43 | 51.33 | 57.04 | 51.17 |
| Monetary ($10^9$¥) | 7.50 | 6.83 | 7.22 | 6.33 | 6.00 | 6.78 |
| Monetary per Volume (¥/m$^3$) | 30.97 | 29.83 | 34.14 | 30.19 | 28.19 | 30.66 |
| **Em¥/m$^3$** | **2.79** | **2.84** | **3.43** | **3.87** | **4.47** | **3.48** |
| **For Agriculture** | | | | | | |
| Emergy ($10^{20}$ sej) | 30.81 | 27.45 | 30.48 | 33.43 | 30.89 | 30.61 |
| Monetary ($10^9$¥) | 4.56 | 4.23 | 4.20 | 4.12 | 3.25 | 4.07 |
| Monetary per Volume (¥/m$^3$) | 5.02 | 4.82 | 5.10 | 5.19 | 4.44 | 4.91 |
| **Em¥/m$^3$** | **0.55** | **0.55** | **0.62** | **0.65** | **0.61** | **0.60** |
| For Residential Life | | | | | | |
| Emergy ($10^{20}$ sej) | 44.20 | 43.90 | 52.10 | 57.20 | 72.60 | 54.00 |
| Monetary ($10^9$¥) | 6.54 | 6.77 | 7.17 | 7.05 | 7.64 | 7.03 |
| Monetary per Volume (¥/m$^3$) | 14.22 | 14.19 | 14.88 | 14.61 | 14.99 | 14.58 |
| **Em¥/m$^3$** | **3.09** | **2.97** | **3.09** | **3.03** | **2.94** | **3.02** |

Source: Wang and He (2015): Emergy—Table **1**; GWCR—Table **7**; Transformity—Table **4**; and Summary—Table **6**.
Symbols: EM—Emergy (R-renewable; N-nonrenewable; F-feedback; EX-export; U-total used)
GWCR—Groundwater Resource (I-industrial; A-agricultural; R-residential)
Transformity = Tr—unit of emergy value (NW-natural water; EW-engineered water; RW-recycled water)

Equation (3) defines the transformational (Tr) properties of different water sources using the unit of emergy value (UEV) in sej/m$^3$ as an efficiency indicator.10 The lower the UEV, the more efficient the system. Equation (3) defines the UEV for three sources of water within Beijing study: natural water (NW), engineered water (EW), and recycled water (RW).

$$UEV_{Source} = \frac{Total\ emergy\ of\ water\ scource\ \left(\frac{sej}{a}\right)}{Mass\ of\ water\ source\ water\ capacity\ per\ year\ \left(\frac{m^3}{a}\right)} \quad (3)$$

For example, an expanded UEV equation for natural water, also classified as watershed rainfall, is defined as:

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[9] The U.S. Dollar to Chinese Yuan spot exchange rate from the Bank of England for the last day of 2008 through 2012 were 6.8225, 6.8259, 6.5900, 6.2944, and 6.2301 respectively. Thus, the Em$ are 46.29, 44.31, 48.51,51.35, and 59.84 ($10^{11}$ sej/$). (https://www.poundsterlinglive.com/bank-of-england-spot/historical-spot-exchange-rates/usd/USD-to-CNY-2012)

[10] See Brown, M. T. and S. Ulgiati (2004).

$$= \frac{\left(\frac{Rainfall}{yr} \times energy_{rain} \times Tr_{rain}\right)}{\left(\frac{Total\ mass\ of\ water}{yr} \div Refresh\ cycle\ time\right)} \quad (4)$$

The UEV for tranformity of the three main sources of water in Beijing (using equation 3) generate the following emergy per volume (sej/$m^3$) values: (a) for tap water 3.34 x 1013 (surface water 3.29 x 1013 and groundwater 3.41 x $10^{13}$), (b) for engineering water 0.32 x $10^{13}$ (surface water 0.23 x 1013 and groundwater 0.35 x $10^{13}$), and recycled water 1.19 x $10^{13}$. See Table **5** (Panel C). Utilizing these values allows for an estimate of the true value of groundwater within the Beijing water district and supports the need for the continuing a sound management of water resources through comprehensive government policies.

Table **5** (Panel D) summarizes Beijing groundwater valuations by source (industry, agriculture, and residential). Monetary values per volume (¥/$m^3$) and Em¥/$m^3$ are the key variables.[11] For the industry subsystem, a low water usage drives a high monetary value per volume. Although it has fluctuated over this 5 year time period, the trend in the last three years is decreasing which shows support for the water savings initiatives that were undertaken during this time period. Within the agriculture subsystem, the emergy and monetary valuations showed slight variations with a noticeable drop in 2012 again supporting the government policy of irrigation coupled with water savings. The residential sector shows an upward trend over time, indicative of the demands of an increasing population on water usage. The emergy monetary value per volume of usage (Em¥/$m^3$) for the industry shows an increasing valuation over time, which is a positive indicator. Both agriculture and residual life are basically flat.

### 3.3. Ranking Water Supply Alternatives—Windhoek, Namibia

Buenfil (2000) documents the decision making process using emergy variables to prioritize three water supply alternatives for Windhoek, Namibia: (1) pipeline, (2) desalination, and (3) groundwater extraction. The author develops extensive diagrams, which build upon our base framework outlined in Fig. (**1**), illustrating the emergy connections. The diagrams highlight the source of the water, transporting mechanisms, benefits to the economy, and environmental impacts.[12] Key results are highlighted in Table **6**. For instance, the emergy monetary value per volume are 0.49, 1.61, and 0.43 Em$/$m^3$ for the pipeline, desalinating, and groundwater options respectively. Buenfil's calculations are based on the renewable resources (river water, sea/brackish water, and groundwater) and the purchased and operational costs such as pipes, electricity, labor, operations, and maintenance.[13] Emergy is one of key factors in their comparison analysis. The water supply system with the lowest emergy/dollar ratio (Em$) per $m^3$ is the most efficient, which in this case is the groundwater option.

Not recorded in Table **6**, Buenfil also considers the potential negative impacts from the development of the three alternatives: 0.487 river pipeline, 0.024 for desalination, and 0.120 for groundwater system (values in Em$/$m^3$).[14] For the pipeline, the negative factors include loss of water, loss of net primary productivity, loss of regional wildlife, and loss of tourism. For the desalination project, the negative effects included loss of seawater, the rain required to dilute the brine, and the loss of shelf net primary productivity. Finally, the negative effects associated with the pumping station include loss of water storage, loss of regional wildlife, and loss of tourism. Negative costs also need to be part of the decision criteria.

Buenfil summarizes the additional key factors supporting the groundwater choice. Four measures that show a preference for increased valuations are percent of renewables (%Renew), emergy yield ratio (EYR), emergy sustainability index, and the emergy benefit to the purchaser (EBP). Each of these values favor the groundwater system. The percent of renewables, where the higher the percent of renewable indicates greater benefits of the project to the environment, supports groundwater at 12.71. EYR represents the competiveness of the alternatives and is calculated as emergy output divided by emergy of all inputs coming from the human economy. An EYR for groundwater at 1.14 is slightly higher than the alternatives. The emergy sustainability index, a ratio of EYR/ELR (where ELR is a measure of the environmental impact of the option), reflects the project's long-run sustainability. The emergy sustainability for groundwater is higher than the alternatives. Finally, the emergy benefit to the purchaser, indicates how much more emergy is delivered relative to the buying power of the payment and again supports the groundwater option.

The valuations, where a lower figure is the best option, include transformity, the emergy investment ratio (EIR), and the environmental loading ratio (ELR). The transformity of the transported water measured in sej/J ranks the projects such that the lower the value, the greater the efficiency of the production process. Groundwater ranks lowest with a value of 1.53 x $10^6$. EIR, a representation of the purchased emergy from the economy divided by the free emergy inputs from the environment (the lower the ratio, the lower the cost), again supports the groundwater option. Finally ELR is calculated as the sum of the local non-renewable resources and the purchased servicers divided by the free renewable resources. Groundwater is vastly superior to the other options. Thus, the emergy variables highlight that water policy should favor the groundwater alternative, but with the caveat that groundwater is not limitless.

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[11] Em¥/$m^3$ valuations are calculated from the data provided Wang and He (2015).

[12] For example, see Buenfil (2004) Figure 2 (Systems diagram of the Kavango River pipeline from Rundu to Grootfontein.

[13] See Buenfil (2000) Table A2 for supporting figures used to generate the total emergy valuations and Table A3 for detailed analysis of the groundwater system. Dollar valuations use 1996 U.S. dollar values.

[14] See Buenfil (2000) Table A4 for support figures such as loss of water, wildlife, and tourism associated with each option.

**Table 6. Emergy Calculations for Water Supply Alternatives in Windhoek, Namibia.**

| | | **Pipeline** | | | **Desalinating** | | | **Groundwater** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Units | | $10^{18}$ sej/yr | $10^3$ US\$/yr | Em\$/m$^3$ | $10^{18}$ sej/yr | $10^3$ US\$/yr | Em\$/m$^3$ | $10^{18}$ sej/yr | $10^3$ US\$/yr | Em\$/m$^3$ |
| Renewable Resource[a] | | 4.0 | 233.6 | 0.010 | 1.9 | 109.4 | 0.010 | 16.4 | 962.1 | 0.048 |
| GRP/Collector Pipeline | | 2.1 | 122.5 | 0.010 | 2.8 | 164.9 | 0.010 | 2.0 | 76.4 | 0.006 |
| Concrete | | 1.4 | 82.4 | 0.005 | 1.7 | 100.8 | 0.010 | 1.1 | 42.7 | 0.003 |
| Fuels | | 0.5 | 29.1 | 0.002 | | | | | 62.4 | |
| Electricity | | 36.6 | 2151.9 | 0.120 | 163.7 | 9629.2 | 0.560 | 33.6 | 1976.5 | 0.099 |
| Machinery & Equipment | | 0.5 | 28.9 | 0.002 | | | | 0.4 | 24.0 | 0.001 |
| Labor, Services & Capital | | 67.4 | 3966.2 | 0.230 | 214.1 | 12591.4 | 0.730 | 73.1 | 4300.0 | 0.215 |
| Operating Costs | | 16.7 | 981.4 | 0.060 | 73.3 | 4311.9 | 0.250 | 13.4 | 790.0 | 0.040 |
| Maintenance Costs | | 16.4 | 962.8 | 0.060 | 15.0 | 881.4 | 0.050 | 5.1 | 300.0 | 0.016 |
| Total[b] | ↓ | 145.5 | 8558.7 | 0.490 | 472.4 | 27789.0 | 1.610 | 145.1 | 8534.1 | **0.430** |
| Transformity (sej/J) | ↓ | 1.78 x $10^6$ | | | 5.76 x $10^6$ | | | **1.53 x $10^6$** | | |
| % Renewable | ↑ | 2.81 | | | 0.40 | | | **12.71** | | |
| EIR | ↓ | 26.09 | | | 131.15 | | | **7.81** | | |
| EYR | ↑ | 1.04 | | | 1.01 | | | **1.14** | | |
| Environmental Loading Ratio | ↓ | 35.64 | | | 252.92 | | | **7.87** | | |
| Emergy Sustainability Index | ↑ | 0.03 | | | 0.004 | | | **0.14** | | |
| Emergy Benefit to Purchaser | ↑ | 1.45 | | | 1.56 | | | **1.58** | | |

Bold indicates best choice.
aPipeline (from Kavango River); Desalinating (sea or brackish water)1.61; and Groundwater.
bEm\$ per m$^3$ of water delivered is recorded in the 3rd column of each process.
Note: ↓ decreasing value better; ↑ increasing value better
Source: Buenfil (2004) Table A2. Emergy evaluation tables for each water supply alternative and Table A5. Comparison of emergy indices among the three water supply systems evaluated.

## 3.4. Water Resource Comparisons—Zhengzhou, China

Lu and Wu (2009) analyze the water resources within Zhengzhou, China versus the regional providence and China in general within three categories: economic development, water resources development, and sustainability. The first category, economic development, is measured by four indicators: renewable investment ratio (RIR), emergy yield ratio (EYR), emergy investment ratio (EIR), and environmental loading ratio (ELR). The latter three ratios were also used in Buenfil (2000). RIR at 2.16% indicates a high degree of non-renewable investments of 97.84% (100% - 2.16%), and thus a potential danger of source exhaustion and environmental destruction. EYR at 60.13 is higher than the province of Henan at 56 and China in general at 9.63 indicating that Zhengzhou is highly competitive since the higher the EYR, the greater the net benefit to society in general. EIR at 2.39% shows under-industrialization compared to more developed cities such as Guangzhou and Hong Kong at 61.58% and 30.02% respectively. Finally, if a project's ELR is too high, then the project may be too emergy intensive and negatively affect the environment. With an ELR at 45.18, which is higher than the province of Henan (31.81) and China (10.54), indicates little room for further development.

The second category analyzed for Zhengzhou's water resources development, is measured by four indicators: water emergy ratio (WER 3.38%), water emergy utilization ratio (WEUR 56.53%), water self-support ratio (WESR 79.77%), and water emergy density (WED 1.31 x $10^{11}$ sej/m2). WER indicates that water accounts for a very low percentage of total emergy, while WEUR indicates that water consumption accounts for over half of these total water resources. WESR points toward the fact that approximately a fifth (20.23%: 100% - 79.77%) of the water usage is dependent on external sources, such as withdrawals from the Yellow River. Finally, a low WED highlights the scarcity of water resources. Policy implications suggest incorporating water conservation and the need for additional water sources to facilitate continued development within the city.

The third category, sustainability, is measured by the water resources population carrying capacity (WPC) and the emergy sustainability index (ESI). A WPC of 193.6 x $10^4$ versus an actual population of 716 x $10^4$ emphasizes the inadequacy of adequate water resources long term. This is supported by the low ESI at 1.33 versus 1.76 for the Henan province which questions the sustainability of the city without additional water resources. This analysis indicates that both regional and national emergy valuations can help determine which locales warrant additional or continued funding.

### 3.5. Watershed Evaluation--Italy

Pulselli, et al., (2011) undertakes an emergy evaluation of an Italian watershed focusing on four river systems (Stura, Upper Sieve, Sieve in Pontassieve, and Arno) and 3 aqueducts (Stura, Pontassieve, and Anconella). Similar to the analysis of Wang and He (2015), their primary evaluation relies on the calculation of unit emergy values (UEVs)—the emergy required to generate one unit of output and a measure of the environmental cost of a given resource. But in this case, the unit of measurement is grams (g) versus cubic meters ($m^3$). The resultant UEVs (sej/g) are recorded in Table **7**. From the river systems, the UEVs value the effort of both the local ecosystem and any man-made infrastructure improvements. The UEVs (sej/g) for the first two river systems have similarly low values (Stura: 1.35 x 105 and Upper Sieve: 1.39 x $10^5$) when compared to the final two river systems (Pontassieve: 5.80 x $10^5$ and Arno 4.32 x $10^5$). The UEVs for the three aqueducts are 2.00 x $10^6$ for Stura, 1.81 x $10^6$ for Pontassieve, and 1.72 x $10^6$ for Anconella. The authors further calculate the emergy investment for purification and distribution of the aqueducts as 1.78, 7.71, and 7.87 (x $10^5$ sej/g) for Stura, Pontassieve, and Anconella respectively. When incorporating water usage, a slight benefit goes to the Anconella plant. Although the latter two plants show increased efficiency versus the small plant at Stura, due to the population density within the region, a larger plant would not be cost effective.

**Table 7. Summary of Unit Emergy Value of Water.**

| **Rivers** | | ***Average Water Flow (g/yr)*** | ***UEV (sej/g)*** |
|---|---|---|---|
| Upper Sieve | | 3.15 x $10^{13}$ | 1.39 x $10^5$ |
| Stura | | 4.06 x $10^{13}$ | 1.35 x $10^5$ |
| Sieve (Pontassieve) | | 3.22 x $10^{14}$ | 5.80 x $10^5$ |
| Arno (Anconella) | | 1.62 x $10^{15}$ | 4.32 x $10^5$ |
| **Aqueducts** | ***Customers*** | ***Water distributed (g/yr)*** | ***UEV (sej/g)*** |
| Stura | 9,000 | 2.48 x $10^{11}$ | 2.00 x $10^6$ |
| Pontassieve | 20,000 | 1.22 x $10^{12}$ | 1.81 x $10^6$ |
| Anconella | 350,000 | 3.33 x $10^{13}$ | 1.72 x $10^6$ |

Source: Pulselli et. el. (2011)

## 4. EXTENSIONS

The next three research papers highlight other areas of emergy research that can be incorporated into future studies. The first study outlines the need for sensitivity analysis, so that not only the past but future expectations can be incorporated into policy decisions. The second study focuses on the use of software to simplify the emergy evaluation. The premise is that if the process becomes more streamlined, it will become easier to encourage governmental units to incorporate emergy valuations into policy decisions. And the third study suggests ways in which emergy could be incorporated into water laws to factor in the effects of climate change.

### 4.1. Sensitivity Analysis—Jiangyin, China

Qi et al., (2018) outlines the use of emergy to evaluate an urban tap water treatment plant in Jiangyin, China and also includes a sensitivity analysis in their study. Another interesting addition to their research is the incorporation of various emergy baselines used within prior research before focusing on the latest update from Brown et al., 2016 (12.00 x $10^{24}$ sej/a). This highlights the need to always include the latest baseline for calculating the emergy related valuations.

Their analysis focuses on six key variables. The first variable, percent of renewable emergy (%Renew), measures the percent of renewable emergy input to the total emergy input. The denominator is an expansion of emergy yield used previously.

$$\%Renew = \frac{R}{R + N + F_R + F_N} \times 100 \quad (5)$$

Where R and FR are local and purchased renewable inputs, respectively; N and FN are local and purchased nonrenewable inputs, respectively. The larger the %Renew, the more sustainable the system. % Renew equals 48.22%, which indicates that 51.78% of the total inputs came from nonrenewable or purchased resources. The second variable, emergy investment ratio (EIR), is define as total purchased renewables divided by total local renewables [i.e., (FR + FN) / (R + N)]. At 1.07388, EIR indicates that purchased inputs have a slightly higher contribution to the tap water system than the free inputs. When the local EIR is greater than the regional EIR, the project may be too energy intensive, which is not the case here.

The third variable similar to UEV discussed in Wang and He (2015), cost per unit pollutant eliminated (CUPE, sej/g), is a ratio to gauge the cost of pollution removal. It is defined as total renewables and nonrenewable divided by the pollutant eliminated [i.e., (R + N + FR + FN) / (Mi) where i represents the pollutant removed]. The higher the value, the higher the cost for eliminating pollutant (i). The CUPE values are 1.89 x $10^{12}$, 2.89 x $10^{13}$, 1.72 x $10^{12}$, and 5.59 x $10^{11}$ for iron (Fe), manganese (Mn), aluminum (Al), and petroleum respectively. The highest removal cost is for the mineral Mn, and the combined extra emergy investment totals 6.61 x $10^{11}$ sej per unit cubic meter of tap water. This variable is used to justify pollution abatement within any water policy.

The fourth variable, the ratio of positive output (RPO), is the total renewables and nonrenewable less the emergy loss caused by the pollution emissions divided by (FR and FN). It is calculated as [(R + N + FR + FN) – F2] / (FR + FN) and equals 1.89876, a value that needs to be compared to competing plants. The fifth variable, the environmental loading ratio (ELR), includes the emissions impact from the industrial process besides the nonrenewable resources consumed. It is calculated as [(N + FN) + R2] / (R + FR), where R2 refers to the ecological service needed to dilute pollution emissions. Using the latest emergy base calculations, ELR equals 1.01125 which is slightly higher than the standard ELR of 1.00973 using the prior emergy base. Both values indicates that the plant has low environmental loading.

Finally, the sustainability index (SI) reflects the ability of a system to provide products or services per unit of environmental stress is calculated as (RPO / ELR). The metric utilized states that if SI is less than 1, then the process is not sustainable in the long term; if $1 < SI < 5$ then it is sustainable short term; and if $SI > 5$, it is sustainable long term. SI equals 1.87763 (versus the SI of 1.91258 using the prior base emergy), which indicates short-term stability. The authors follow these initial calculations up with a sensitivity analysis focusing on the independent factors FN and R while ignoring FR due to its small contribution to total emergy input. FN has the highest impact on SI, followed by ELR, EIR, %Renew, and RPO. Results for R are similar in that the highest impact is on SE but followed by EIR, ELR, %Renew, and RPO. In the policy process, sensitivity helps place the focus on the variables that have the most impact on the underlying decision. It also offers the opportunity to focus the analysis on what might change in the future. Which is becoming more important as climate change accelerates.

### 4.2. Software Analysis--Mexico

The contribution of Fonseca et al., (2017) is the framework of a software system used to simplify the emergy evaluation process through a case study of the Lerma River in Mexico. This is an extension of research conducted by Diaz-Delgado et al., (2014). The software improves the evaluation process by allowing scenario and sensitivity analysis to be undertaken for environmental changes such as for periods of droughts or excessive rain. The scenario analysis permits the assessment of the economic impact and the environmental sustainability within the analyzed city or region more fully. Within their analysis, they assess the extraction of groundwater and the treatment of both surface and groundwater for subsequent use to a variety of constituents (agricultural, industrial, and urban). Their findings show that the current aquifer is inadequate for future needs and water needs should transition to wastewater treatment plants as a viable option.

### 4.3. Water Laws

Unlike the previous examples that attempted to measure the value of various water alternatives, Hill-Clarvis et al., (2013) lays out an argument that laws governing the allocation of water rights need to be updated to incorporate the effects of climate change. They advocate the need for iterativity, flexibility, connectivity, and subsidiarity. The use of emergy calculations have the potential to improve the evaluation within all four dynamics. The first factor, iterativity, deals with generation, processing and application of knowledge. The key is to incorporate variable rights which are subject to environmental and social changes. The second factor, flexibility, involves the willingness and capacity to adjust to changing conditions and new information. Key aspects include emergency provisions during droughts and floods and risk apportionment across different constituents. The third factor, connectivity, deals with networks and connections applied to integrated and tiered water use licensing. Finally the fourth factor, subsidiarity, applies to the implementation of policies to insure water rights to the most marginal constituents. They stress that any decisions relying on emergy analysis needs to be supported by conventional economic and energy analysis. Several discussion points outlined by the authors include: the need for setting periodic reviews; variable rights; permits; entitlement issues; water rights trading; administration of policies; standards; and active monitoring.[15]

## 5. CONCLUSION

As outlined within this study, emergy is being used in a number of settings for water strategies such as valuation, prioritizing projects, and evaluating policy initiatives. The examples highlighted illustrate two key points. First, how a select number of valuations and ratios that employ the emergy concept can be utilized depending upon the problem being analyzed. The key calculations include an emergy yield ratio (EYR), a percent of renewable emergy (%Renew), an emergy investment ratio (EIR), an emergy currency per volume ratio (Em\$/$m^3$ and Em¥/$m^3$), and a transformity factor. The first two variables are increasing functions, i.e., an increasing value indicates a more beneficial outcome. The latter three valuations are decreasing functions, i.e., the lower the value the greater the benefit of the underlying process. These emergy based valuations are shown to complement water policy decisions beyond typical cost benefit analysis. If the major concern is appropriate use of resources and long run viability, then EIR, EYR, and the %Renew should have the most relevance for policy implications. But, if the emphasis is on efficiency and the least emergy cost, then transformilities and emergy costs (Em\$/$m^3$) are the more appropriate variables.

Second, extensions in the literature highlight the need to seek improvements in the decision making process through simulations, scenario analysis, software development, and the underwriting of laws that capture the true valuation of water. One key trend is to make sure that the emergy calculations are based upon the latest data including transformations and monetary units. By illustrating how different countries are making sound water policy decisions based on emergy results, this review reinforces the fact that emergy analysis can

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[15] See Hill-Clarvis et. el. (2013) Table **2** for a summary of the challenges and proposed solutions science-law mismatches.

be incorporated into long-term water policy and implementation.

## CONFLICT OF INTEREST

The author states that there is no conflict of interest due to a personal relationship with a third party.

## GLOSSARY

| | **Emergy** | **Generally, available energy of one kind previously required directly and indirectly to make a product or service (units: emjoules, emkilocalories, etc.). Specifically, solar energy required directly and indirectly to make a product or service [units: solar emjoules (sej)]** | |
|---|---|---|---|
| R | Renewable Emergy | The "free" renewable emergy required in a production process (e.g., rain and sun for agriculture). | |
| N | Nonrenewable Emergy | The "free" nonrenewable emergy required in a production process (e.g., rain and sun for agriculture). | |
| F | Purchased Emergy Inputs | The sum of human services (S) and the goods, fuels, and energy (P) required in a production process. | F = S + P |
| Y | Emergy Yield | The sum of all emergy inputs to produce a product or generate a service. | |
| EIR | Emergy Investment Ratio | The purchased emergy feedback from the economy (F) divided by the free inputs from the environment (R+N) | EIR = F / (N+R)<br>= (P+S) / (N+R) |
| EYR | Emergy Yield Ratio | The emergy of the output (Y) divided by the emergy of all inputs coming from the human economy (F) | EYR = Y / F<br>= Y / (P+S) |
| %Renew | Percent renewable emergy | The ratio of the renewable emergy to emergy yield times 100. | %Renew = (R / Y) * 100 |
| Em$ | Em-dollar ratio | The emergy-based monetary value of a product, resource, or service, which is obtained by dividing the emergy of something by the emergy/money ratio for a particular currency of a particular year. | |
| Em$/m$^3$ | Dollar value per volume | Em-dollar value of water per cubic meter of water | |
| Tr | Transformity | In general, emergy per unit available energy of one kind. Specifically, solar emergy per unit available energy (units: solar emjoules per joule (sej/J)] | |
| UEV | Unit emergy value | A measure of efficiency for the transformity of different water bodies | $UEV_x = \frac{Total\ emergy\ of\ x\ \left(\frac{sej}{a}\right)}{Mass\ of\ water\ capacity\ per\ year\ of\ x\ \left(\frac{m^3}{a}\right)}$ |

Source: eMergy Evaluation by Howard T. Odem, Paper presentation at the International Workshop on Advances in Energy Studies: Energy flows in ecology and economy. 1998. (http://dieoff.com/page170.htm)

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