# Optimizing the management of microirrigation systems

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Taller de Microriego: Logros y enseñanzas del proyecto regional H-402 (W3128)
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**Abstract**

Since the inception of the USDA H-402 (W-3128) Project, several studies have been conducted related to *crop water use and management of drip irrigation*. An evapotranspiration (ET) station was designed and compared to eddy-covariance systems in Florida and Puerto Rico. The new equipment performed well and could be produced for a fraction of the cost of traditional field ET measurement equipment. A three-year study employed the ET-Station in southern Puerto Rico where crop coefficients were derived for two varieties of common bean. Recently, a research project was conducted in which an operational water and energy balance algorithm called GOES-PRWEB was developed based on 1-km resolution satellite-derived solar radiation. GOES-PRWEB data are published daily for Puerto Rico, and can be used by the scientific community, private companies and citizens, and the government. Reference ET and the related input variables are also published each day for the islands of Puerto Rico, the U.S. Virgin Islands (USVI), Hispaniola, Jamaica and Cuba. Recent outreach efforts have resulted in an online procedure for scheduling irrigation at any location within the seven islands mentioned above. Efforts have also supported irrigation management surveys, Capstone student projects related to irrigation scheduling mobile app development, installation and maintenance of meteorological equipment and the design and installation of micro irrigation systems at the UPRM Finca Alzamora.

**Introduction**

Under-application of water can result in a reduction in crop yield, while over-application of irrigation can result in the loss of water, fuel, pesticides, fertilizer and crop yield, and may contaminate surface or groundwater (Harmsen et al., 2018). There is an optimal amount of water a crop needs to achieve maximum yield. This amount is equal to the crop evapotranspiration rate ($ET_c$). The $ET_c$ assumes well-watered conditions and therefore $ET_c$ is a potential evapotranspiration. Typically, $ET_c$ is estimated from the equation $ET_c$=$K_c$ $ET_o$, where $K_c$ is the crop coefficient and $ET_o$ is the reference evapotranspiration. $K_c$ is a function of the crop physiology (e.g., stage of growth, roughness, color, stomatal resistance, etc.), while $ET_o$ is a function of the climatic conditions (e.g., net radiation, air temperature, dew point temperature and wind speed). When $ET_o$ is estimated using the Penman Monteith equation (Allen et al.,1998), it applies specifically to a hypothetical reference crop with an assumed crop height of 0.12 m, an albedo of 0.23, a fixed surface resistance of 70 sec $m^{-1}$, and an aerodynamic resistance equal to $208/u_2$, where $u_2$ is wind speed at 2 m height.

Insufficient water reduces crop yields due to water stress, which can adversely affect photosynthesis, respiration, translocation, ion uptake, carbohydrates, nutrient metabolism, and hormones (Lisar et al., 2012). Over application of water can also reduce crop yield due to saturated soil conditions, which interferes with root respiration, or may be due to the leaching of fertilizer from the root zone. When the actual or real evapotranspiration ($ET_a$) is less than $ET_c$ crop stress will occur.

Most of the studies described below aimed at estimating or measuring evapotranspiration. By estimating $ET_c$ it is possible to determine the proper amount of irrigation to apply to maximize crop yields, while estimating or measuring the $ET_a$ allows estimation of crop stress and the consequent reduction in crop yield.

**Review of Projects**

Harmsen et al. (2009) developed a field methodology for estimating actual ET. The goal of the project was to develop an instrument that provided accurate ET but at a much lower cost than eddy covariance or weighing lysimeter systems. The "ET station" consisted of a movable temperature and humidity sensor raised and lowered between two vertical positions at two-minute intervals (twelve readings at each position) to obtain the humidity gradient. In the theoretical formulation, a humidity gradient flux equation (Monteith, 2008) is equated with the generalized Penman Monteith (GPM) equation (Allen et al., 1998, equation 3) and resolved for the bulk surface resistance ($r_s$). Once $r_s$ is obtained, all parameters and variables were available for estimating ET using the GPM method. The instrument was compared against an eddy covariance system at the University Florida Agricultural Experiment Station near Gainesville Florida in 2004 and at the University of Puerto Rico Agricultural Experiment Station at Lajas, Puerto Rico in 2005. The ET station compared favorably with the eddie covariance systems. The advantage of the ET station is that its cost is approximately 1/7 the cost of an eddie covariance system and about 1/20 of the cost of a weighing lysimeter.

As part of his M.S. research project, Ramirez (2007) conducted several ET studies for common bean (*Phaseolus vulgaris* L.) in Puerto Rico, with topics including: development of linear models for non-destructive leaflet area estimation; physiological response of different common bean genotypes to drought stress; ET and crop coefficients for two common bean genotypes with and without drought stress; surface resistance estimates from micro-meteorological data; crop measurements under variable leaf area index and soil moisture; crop water stress indices and yield components for common bean genotypes in greenhouse and field environments; and water use efficiency and transpiration efficiency for the two common bean genotypes. [See also Ramirez et al. (2011); Ramirez et al. (2006); Porch et al. (2009); Ramirez et al. (2008a and 2008b)].

Harmsen et al. (2009) conducted a study to estimate precipitation (P), reference evapotranspiration (ETo), precipitation deficit (PD = P - ETo) and relative crop yield reduction (YR) for a generic crop under climate change conditions for three locations in Puerto Rico: Adjuntas, Mayagüez and Lajas. Reference evapotranspiration was estimated by the Penman–Monteith method. Precipitation and temperature data were statistically downscaled and evaluated using the Department of Energy

NCAR PCM global circulation model projections for the B1 (low), A2 (mid-high) and A1fi (high) emission scenarios of the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios. Relative crop yield reduction was estimated from a water stress factor, which is a function of soil moisture content. Average soil moisture content for the three locations were determined by means of a simple water balance approach.

Results from the analysis indicated that the rainy season will become wetter and the dry season will become drier. The 20-year average September precipitation excess (i.e., PD > 0) increased for all scenarios and locations from 121 to 321 mm between 2000 and 2090. Conversely, the 20-year average February precipitation deficit (i.e., PD < 0) changed from -27 to -77 mm between 2000 and 2090. The results suggest that additional water could be saved during the wet months to offset increased irrigation requirements during the dry months. The 20-year average relative crop yield reduction for all scenarios decreased on average from 12% to 6% between 2000 and 2090 during September but increased on average from 51% to 64% during February. Information related to the components of the hydrologic water budget (i.e., actual evapotranspiration, surface runoff, aquifer recharge and soil moisture storage) were also evaluated. The study provides important information that may be useful for future water resource planning in Puerto Rico.

Collaboration was initiated in 2009 between the University Puerto Rico and the University of Alabama in Huntsville, resulting in the availability of a remotely sensed solar radiation product for the northern Caribbean region (Harmsen et al., 2014a). Solar insolation estimates are developed from GOES visible data at 1 and 2-km resolution over Puerto Rico and the Caribbean, respectively, and are provided at 30-min time frequency each day (~5 am through 8 pm Local Time). The methods of Gautier and Diak (1980), Diak et al. (1996) and Paech et al. (2009) are utilized, with validation of the solar insolation provided in Otkin et al. (1995) and Mecikalski et al. (2011). These GOES solar radiation data are a critical input parameter for $ET_o$ equations. As noted, the spatial resolution of the GOES product is 2-km, however, there is a sub-set of data available for Puerto Rico and the US Virgin Islands, which provides 1-km spatial resolution that is critical for obtaining accurate insolation estimates between cumulus convective clouds (see Paech et al., 2009). The remotely sensed solar radiation product represents a valuable tool for Puerto Rico, because prior to 2009 there were very few solar radiation sensors distributed across the island.

Harmsen et al. (2009) developed a geographic information system for $ET_o$, based on remotely sensed solar radiation, which included estimates of the Penman-Monteith (Allen et al., 1998), Hargreaves radiation (Hargreaves, 1975; Hargreaves and Samani, 1985) and Priestly and Taylor (1972) methods, all based on remotely sensed solar radiation (Harmsen et al., 2014a). Currently the algorithm produces daily reference ET for Puerto Rico, the USVI, Hispaniola, Jamaica and Cuba. Figure 1 shows an example of daily $ET_o$ for the seven islands for Sep 13, 2015 (PM method only). The daily $ET_o$ images are available at a public website (http://pragwater.com/daily-reference-evapotranspiration-eto-for-puerto-rico-hispaniola-and-jamaica/) from January 1, 2009 through the present.

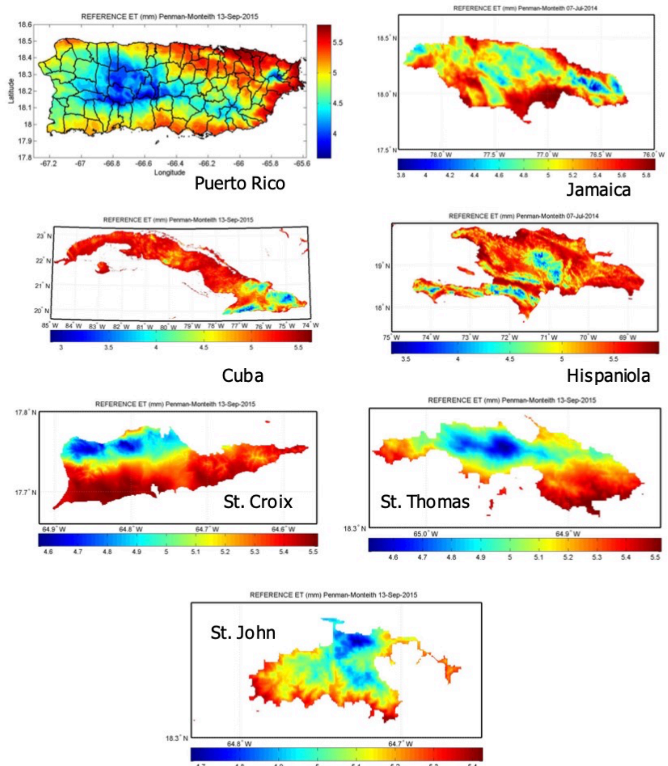


Figure 1. Reference Evapotranspiration Estimate (Penman-Monteith method) for September 13, 2015 for Puerto Rico, USVI, Hispaniola, Jamaica and Cuba.

Harmsen et al. (2010) modified the algorithm described in the previous paragraph to include the water and energy balance components. The algorithm is called the Geostationary Operational Environmental Satellite-Puerto Rico Water and Energy Balance or GOES-PRWEB. The water balance is based on the actual ET, which is estimated at 1-km spatial resolution. Actual ET is derived from an energy balance approach similar to the methodology described by Yunhao et al. (2001). Surface runoff is estimated using the Natural Resource Conservation Service Curve Number (CN) method (Fangmeier et al., 2005). Rainfall is obtained from the National Oceanic and Atmospheric Administration's (NOAA's) Advanced Hydrologic Prediction Service (AHPS) website. Soil moisture is estimated using a simple soil reservoir concept (e.g., Harmsen et al. 2014b) in which infiltrated water in excess of the field capacity becomes aquifer recharge. Figure 2 shows examples of the energy and water balance components, respectively, for Nov 24, 2015. Images for twenty-eight hydro-climate variables are available on a public website (http://pragwater.com/goes-puerto-rico-water-and-energy-balance-goes-web-algorithm/).
Archived images and data (csv and Matlab formats) are available from January 2009 through the present.

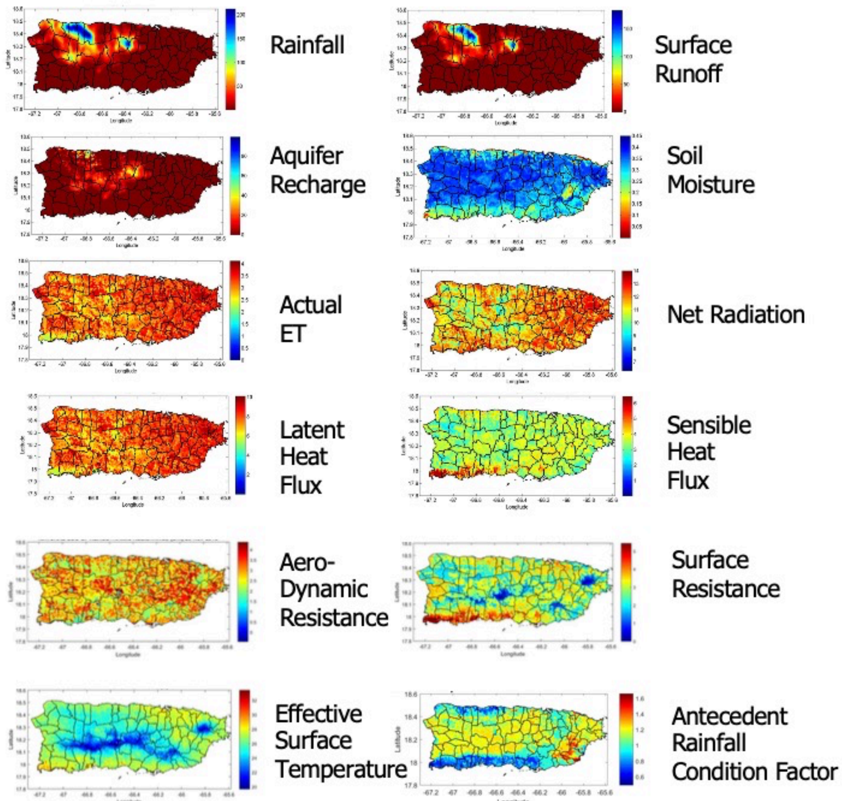


Figure 2. Example of water and energy balance components from the GOES-PRWEB algorithm for November 24, 2015.

In 2011 the PRAGWATER website (https://pragwater.com) was launched, with the primary goal of providing downloadable results from GOES-PRWEB and remote sensing solar radiation data. Figure 3 shows the website homepage. The site provides the pragwater blog and information on PR drought, solar radiation, GOES-PRWEB, $ET_o$ for the northwest Caribbean, publications, UPRM-Finca Alzamora weather, software, etc.  The solar radiation resource is very popular with most downloads of the hourly or daily data being used to design solar energy systems. The average views per month for the $ET_o$ and solar radiation pages are 39 and 132, respectively.

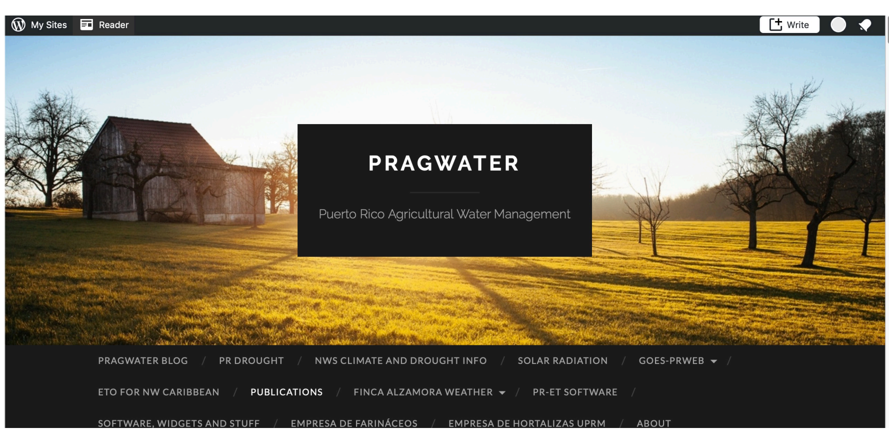


Figure 3. pragwater.com homepage.

Harmsen (2012) developed a web-based methodology for irrigators to schedule their irrigation based on the daily $ET_o$ estimates for Puerto Rico, USVI, Hispaniola, Jamaica and Cuba. The goal for the methodology is to assist irrigators to replace crop ET (i.e., $K_c$ $ET_o$) with irrigation (or rainfall) throughout the crop season. In Puerto Rico, the user can access NOAA's AHPS rainfall data if they do not have a rain gauge on their farm.

Harmsen et al. (2014a) reported a study in which ground-based sensors at the UPR Fortuna Experimental Station and the University of Puerto Rico-Mayagüez Campus (UPRM), were used to calibrate daily-integrated satellite-derived solar radiation. The calibration equations yielded $R^2$ values of 0.88 and 0.83 at Fortuna and Mayagüez, respectively. A regression equation was also derived based on the combined data from the two locations with an $R^2$ of 0.87. The calibration equations for Fortuna and UPRM were validated using 283 and 227 days of solar radiation data from 2010, respectively. At the study sites, the uncorrected data produced reasonably accurate results with a maximum 6.22% error between the mean estimated and measured solar radiation. This study did not consider areas of the island defined as humid-mountainous, and therefore, future calibration/validation efforts should focus on this environment.

Results from GOES-PRWEB have shed light on the impacts of the Puerto Rico drought of 2015. The eastern half of the island was the most severely impacted. Many of the island's water supply reservoirs dropped to levels not seen since the devastating drought of 1994. In response to the smaller drought of 2014, the Government established the Puerto Rico Technical Scientific Drought Committee, whose task was to provide short and long-term recommendations to the Governor of Puerto Rico and Agency Secretaries, with the goal of improving the island's response to extreme drought events. Participants on the Committee included representation from Federal and Commonwealth Agencies as well as the Puerto Rico Electric Authority, Puerto Rico Aqueducts and Sewer Authority and the UPRM. The Drought Committee uses soil/water data and crop stress information produced by GOES-PRWEB, and the National Weather Service uses soil moisture and root zone soil moisture saturation on their Climate and Drought Information webpage (https://www.weather.gov/sju/dss_climo).

As an example of GOES-PRWEB results provided to the Drought Committee during the 2015 drought, Figure 4 shows the rainfall deficit, here defined as the P-$ET_o$. Only negative values of the deficit are shown, the white areas representing excess rainfall. Large monthly deficits over 100 mm were observed at numerous locations throughout the island, however, there were numerous municipalities in the northwest part of the island that had excess rainfall during all months in 2015.

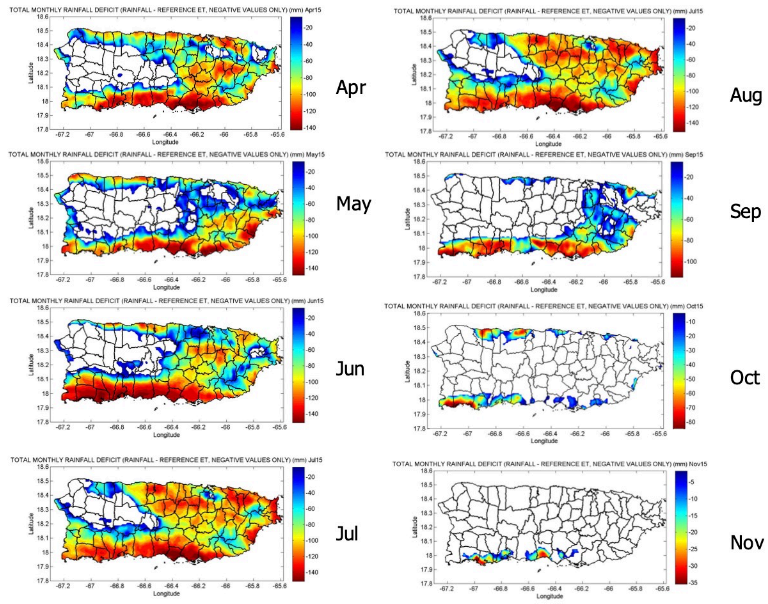


Figure 4. Monthly rainfall deficit (P-ETo) for Puerto Rico during the 2015 Drought. White areas represent excess rainfall (i.e., no rainfall deficit).

Harmsen (2018) developed a simple spreadsheet method for scheduling irrigation. The water balance method used is based on the methodology of the United Nations (UN) Food and Agriculture Organization (FAO). Soil moisture is depleted from the soil profile by evapotranspiration. By maintaining the soil moisture content between the field capacity and the threshold moisture content, water stress can be avoided and 100% of the potential yield can be achieved, ignoring reductions in yield due to other factors such as fertility, disease, and salinity. The method provides an estimate of the crop stress factor, from which the relative seasonal yield can be estimated for many crops. Several graphs are provided in the spreadsheet, which help the user evaluate their real-time water management. In addition to estimates of the relative yield, the spreadsheet also provides an estimate of the lost irrigation (i.e., irrigation lost to surface runoff or deep percolation). Harmsen (2018) provided two examples for a farm growing bell peppers, located near Juana Diaz, Puerto Rico. The irrigation scenarios considered were 1-inch per week and optimal irrigation. With the use of Figure 5 and Table 1, it is possible to estimate potential yield losses and loss in dollars per acre for fifteen crops in Puerto Rico. The economic information used to develop Table 1 was based on model budget data from the "Conjunto Tecnológico" of the UPR Experiment Station.

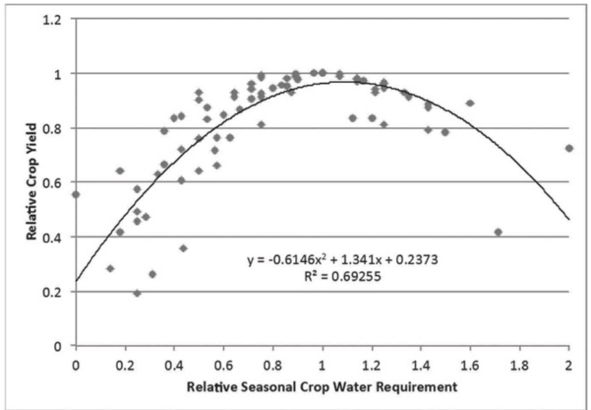


Figure 5. The relationship between the relative crop yield and the relative seasonal crop water requirement.

Table 1. Amount, in dollars, lost per acre as a percentage of crop water requirement applied.

| | Percentage of Crop Water Requirement Applied | | | | | | |
|---|---|---|---|---|---|---|---|
| | 40 | 50 | 80 | 100 | 130 | 150 | 180 |
| CROP* | $ Lost / Acre | | | | | | |
| Gandules | 47 | 32 | 10 | 0 | 12 | 35 | 69 |
| Pepinillo | 111 | 76 | 25 | 0 | 15 | 56 | 124 |
| Repollo | 256 | 174 | 57 | 0 | 21 | 103 | 247 |
| Sandia | 293 | 199 | 65 | 0 | 23 | 114 | 277 |
| Platanos y Guineos, Plantilla | 318 | 216 | 71 | 0 | 24 | 122 | 299 |
| Calabaza | 390 | 265 | 87 | 0 | 27 | 146 | 359 |
| Cebolla | 543 | 369 | 121 | 0 | 34 | 195 | 490 |
| Pimiento | 578 | 393 | 129 | 0 | 36 | 206 | 519 |
| Barenjena | 757 | 514 | 169 | 0 | 44 | 264 | 670 |
| Platanos y Guineos, Reton~o | 1,006 | 684 | 225 | 0 | 76 | 388 | 945 |
| Melon, Cantaloupe y Honeydew | 1,027 | 698 | 229 | 0 | 56 | 352 | 899 |
| Raices y Tuberculos | 1,041 | 707 | 232 | 0 | 57 | 356 | 911 |

To better understand the current practices of irrigation scheduling in Puerto Rico, two surveys were conducted in southern PR. The first survey was conducted at an irrigation training activity at the Fortuna Experiment Station in 2014. Of the 60 people who responded to the survey, the results indicated that 35% based their irrigation schedule on "experience" 35% used the soil moisture method, 8% use the evapotranspiration method, 3% use the water balance method and 19% use some "other" method. Combining "other" with "experience", and further assuming that these constitute non-scientific methods, the survey suggested that more than half of the farmers surveyed are not using scientific methods to schedule their irrigation.

The second survey was conducted in Salinas, PR in late 2018. Fourteen irrigators took part in the survey. The results indicated that 92.9% used the soil moisture method, 0% used the evapotranspiration method, 0% used the water balance method and 7.1% used "experience". Although the results of the second survey are encouraging, the sample size was quite small, and the participants were all from a single municipality.

Other activities in support the H-402 project included:

1. Provided guidance to two Software Engineering Capstone project groups. The goal of both groups was to develop a mobile app to assist farmers to schedule irrigation. Both groups

produced excellent mobile app products (PRAGMA and H2OCrop), but unfortunately, after the semester projects ended, the students were no longer available to finalize and launch the mobile apps to the public. Currently, Puerto Rico is still in need of this type of technology to assist farmers with their irrigation management.

2. Installation and maintenance of two weather stations and an eddy covariance flux tower in the UPRM Finca Alzamora.
3. Provided recommendations for improvements to the Corozal Experiment Station irrigation system.
4. Designed and installed two micro irrigation systems in the Ecological Farm of the UPRM Finca Alzamora.

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