Are Best-Management-Practice Criteria Really Environmentally Friendly?

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Abstract: In the 1990's, a number of best management practices (BMPs) manuals have been developed that address the control of urban runoff to protect receiving water quality. More recently, several papers have investigated the effectiveness of these BMPs in protecting small urban watercourses, and have concluded that they do not. Investigations of both design practices and effectiveness reveals that there is a lot of ignorance in the scientific and engineering community about what constitutes a properly designed BMP and what it really achieves, with respect to environmental protection. This paper discusses the state-of-practice in BMP design in the United States and points out its strengths and weaknesses with respect to real protection of the downstream receiving water environment. The paper recommends an approach to design criteria development that can be applied over a wide variety of climatologic, topologic, and geologic conditions to protect receiving waters systems.

INTRODUCTION

In the 1990's, so called Best Management Practices (BMPs), have been used more and more to control the pollution of urban runoff and ostensibly protect the receiving waters to which the runoff drains. More recently some investigators [e.g. Maxted and Shaver (1997) and Schueler (1999)] have offered opinions that these BMPs do not protect the downstream aquatic environment, and Schueler (1999) now argues that a different approach to management of urban runoff is required to protect urban streams. However, it is the writers' opinion that the problem is not the BMPs themselves, but rather that the design guidance for BMP outlet flow control does not take into account the geomorphologic character of the stream. This paper examines these issues and provides comments for improving the design of BMPs so that they are more friendly to the environment. The paper is directed at urban headwater streams, not larger streams or rivers that flow through an urban area.

IMPACT OF URBANIZATION ON RUNOFF

The effect that urbanization has on a watershed (Fig. 1) has been well documented in the literature, but we cover the highlights here again as background for the subsequent discussion. Undeveloped land has very little surface runoff; most of the rainfall soaks into the top soil and evapotranspirates or migrates slowly through the soil mantle as interflow to the stream, lake, or estuary. As a result of this process, rainfall effects are averaged out over a long period of time (Fig. 1). But as a watershed develops and the land is covered over with impervious surfaces (roads, parking lots, roofs, driveway, and sidewalks), most of the rainfall is transformed into surface runoff.

The resulting effect on the hydrology of the receiving water is dramatic, especially for streams. A given rainstorm now produces significantly more runoff volume than before, and flow peaks are increased by a factor of 2 to more than 10. The overall hydrologic effect is that the flow frequency curve for a developed area is significantly higher than for an undeveloped area as shown in Fig. 2. This change in the flow frequency curve manifests itself in two ways. First, as just mentioned, the peak runoff rate for a given return period storm (rainfall) increases (point A in Fig. 2). In the Metropolitan Denver (Joint Task Force 1998) area these increases range from a factor of 2 to 60 as illustrated in Table 1. The extremely high increase in the two-year peak runoff is due to the fact that predevelopment runoff was nearly zero. In other localities the increase may not be as dramatic, but in general, the percentage increase in the peak flow is highest for small, frequent storm events as Fig. 2 illustrates.

The second effect that urbanization has on runoff is to significantly increase the frequency of the predevelopment peak flows (point B in Fig. 2). Impacts reported by Schueler (1987), in Maryland are illustrated in Table 2. The table shows that the two-year peak runoff rate in the predeveloped state occurs three times per year if the area is developed as residential, and eight times per year if the area is developed as industrial property. This is an increase in frequency of 6–18 times!

FLOW IMPACTS ON RECEIVING WATERS

The increased magnitude and frequency of these flow peaks can cause severe stream channel erosion and increased flooding downstream. The most commonly observed effects are the physical degeneration of natural stream channels. The higher frequency of the peak flows causes the stream to cut a deeper and wider channel (Fig. 3), degrading or destroying the instream aquatic habitat. The eroded sediments are deposited downstream in slower moving reaches of the stream or at the entrance to lakes or estuaries, harming the aquatic habitat in these areas by smothering the benthos, filling wetlands with sediment, and so forth. As a result of the erosion and sedimentation, decreases in biodiversity and numbers of aquatic stream biota are commonly observed in both areas.

The hydroperiod of the wetlands in these watercourses are also drastically changed, experiencing high flows for short periods during and after rainfall, followed by a period of much reduced or zero flow, due to the reduction of interflow. Freshwater wetlands can dry up or become unsightly bogs. Saltwater wetlands will deteriorate due to the increases in the frequency of large freshwater flow into them, or they may convert to freshwater wetlands if the rainfall frequency is high enough to keep a supply of freshwater running through them. The effect of these changes in the wetland causes significant stress

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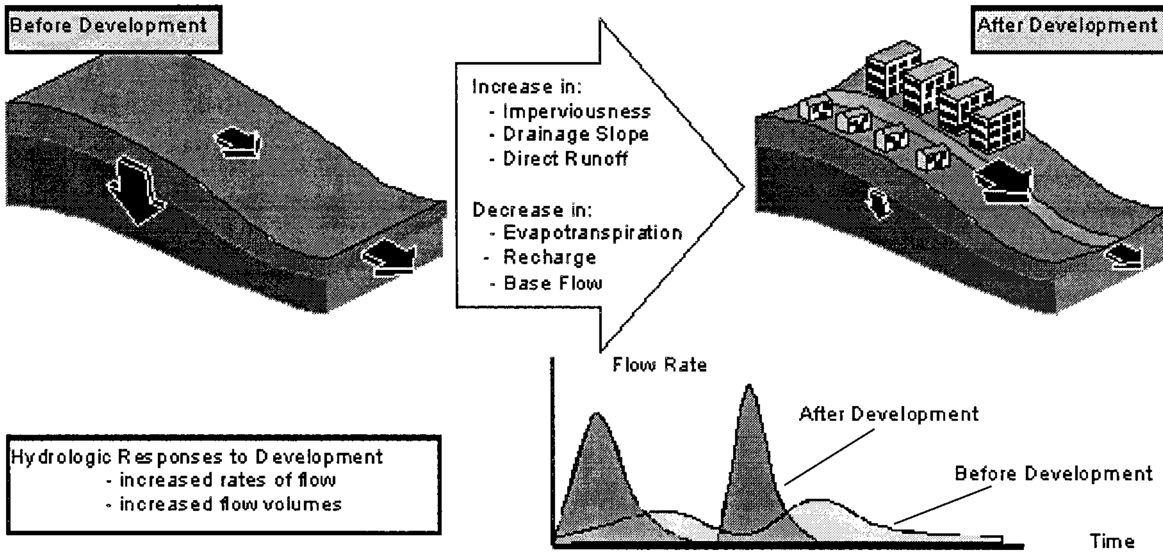

FIG. 1. Urban Impacts on Hydrology

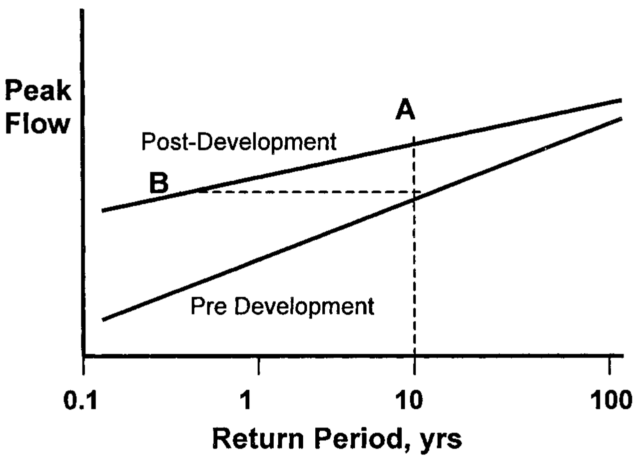

FIG. 2. Effect of Urbanization on Flow Frequency Curve

FIG. 3. Typical Channel Erosion due to Urbanization

TABLE 1. Impact of Urbanization on Peak Flow Rate (Joint Task Force 1998)

Storm	Ratio of postdevelopment to predevelopment flow peak
100-year	×2
15-year	×3
2-year	×57

TABLE 2. Increase in Frequency of Two-Year Peak Runoff Rate due to Development (Joint Task Force 1998)

Percent impervious	Frequency (times/year)
30 (residential)	3
50 (strip comm)	6
80 (industrial)	8

to the native biota, resulting in loss in biodiversity and often changes of species.

WATER QUALITY IMPACTS OF URBANIZATION

The principal constituents of concern in urban runoff are total suspended solids (TSSs), nutrients (P and N), heavy metals (Cu, Pb, and Zn) and fecal bacteria (*E. coli*). The first comprehensive reporting of typical concentrations of these parameters in urban runoff was the USEPA National Urban Runoff Program (NURP) conducted in the late 1970s and early 1980s (USEPA 1983). Since then many investigators have reported results of newer testing; these later measurements show only slight variations from the USEPA data.

It is the writer's opinion that, while typical storm water can have negative impacts on the health of an urban aquatic ecosystem due to the pollutants contained in the runoff, those effects are generally masked by the negative habitat impacts caused by uncontrolled runoff. Therefore, urban runoff management programs should target flow control first. If this is properly done, the quality issue will for the most part resolve itself, because the flow management practices that must be employed will generally result in removal of pollutants from the runoff.

CONTROLLING FLOW FREQUENCY CURVE WITH TRADITIONAL DRAINAGE PRACTICE

Design for Flood Control

Urban hydrologists and drainage engineers have long acknowledged the fact that flows increase as a result of development. Many municipalities now have ordinances requiring that larger storms be controlled so the postdevelopment peak flow for a given return interval storm (rainfall event) does not exceed the predevelopment peak flow for that same storm. The state of Florida requires that such control be provided for the 25-year storm. Other places in the United States require that the 10-year storm is controlled to predevelopment levels; and a few municipalities require that postdevelopment discharges not exceed the predevelopment 2-year storm for all storms. To the writers' knowledge, no municipality requires that storms less than the two-year storm be controlled to predevelopment levels.

To achieve this control, the most common practice is to use detention basins to peak shave the postdevelopment flow so that basin outflow does not exceed predevelopment flow for the design storm. The basic effect of peak shaving on the outflow hydrograph is illustrated in Fig. 4. But experience with these facilities shows that while they reduce downstream flooding, they are not effective at reducing the erosion in stream channels for two reasons. The first is due to the protracted time of flow at the lower rate, as illustrated in Fig. 4. If the basin outlet flow is large enough to cause stream bank erosion in the downstream channel, the detention basin actually subjects the stream channel to the erosive flows for a longer period of time. This has led some geomorphologists to suggest that flow attenuation should not be practiced for runoff peaks except as absolutely required for flood protection downstream. But, this would be difficult to administer in a developing community, and thus is probably not practical.

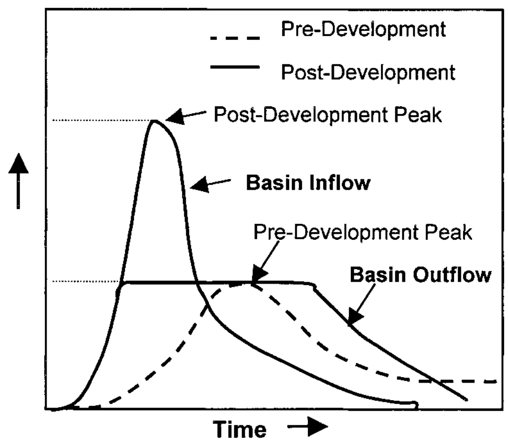

FIG. 4. Effect of Peak Shaving on Detention Basin Outflow Hydrograph

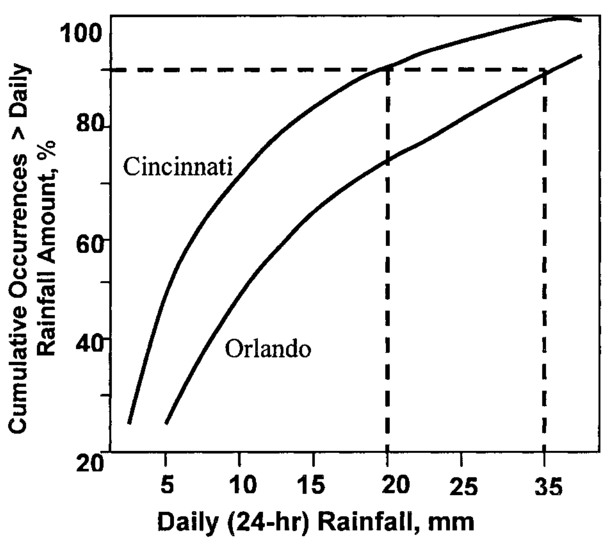

FIG. 5. Cumulative Rainfall Distribution for Orlando, Fla., and Cincinnati

TABLE 3. Comparison of 25-Year Rainstorm with 90th Percentile Storm

City	25-year, 24-h rainfall (mm)	90th percentile 24-h rainfall (mm)
Cincinnati	74	20
Orlando, Fla.	127	36

The second problem with flow attenuation, as it is generally practiced, is that the outlet works for these basins are designed only to attenuate the flow of the design storm. Any flow attenuation that occurs for other storms is purely coincidental. For those storms that have postdevelopment runoff peaks smaller than the basin outlet capacity, very little flow attenuation takes place. Thus, given the increased frequency of peak flows in general, and the fact that most detention basins do not regulate flows smaller than the 10 year predevelopment flow, most storms will pass through the structure unregulated, subjecting the downstream channel to erosive velocities on a more frequent basis. To illustrate this, Fig. 5 shows the cumulative frequency plots of daily rainfall amounts for Orlando, Fla., and Cincinnati. The curves show that 90% of the annual rainfall comes in storms smaller than 20 mm in Cincinnati and 36 mm in Orlando. Table 3 compares these volumes to the 25-year storm for both cities. Table 3 reveals that the 25-year storm is nearly four times the volume of the 90th percentile storm for both cities. This is why flood control facilities have very little effect of the runoff hydrograph of most storms.

Examination by Roesner (1999) of five other U.S. cities plus Edinburgh, Scotland, with widely varying climatic conditions confirms that most of the annual rainfall occurs in small storms. Table 4 identifies the cities and the capture volume required for 90% control of the annual volume of runoff. These capture volumes were determined by hydrologic simulations using STORM (Roesner et al. 1974; *Storage* 1976) with multiyear, hourly rainfall records as input. The computed runoff was routed through capture (detention) facilities of various sizes (volumes), using a constant facility release rate equal to the storage volume divided by 24, i.e., the drawdown time for a full basin is 24 h—this criteria is commonly used for BMP detention facilities intended to settle out suspended solids in urban runoff. Table 4 shows that a unit storage volume of roughly 5–15 mm (except for San Francisco, which requires 23 mm) is sufficient to capture 90% of the annual runoff in the BMP facility.

Design Storm for BMPs

The recommended design storm for sizing most BMPs is the storm volume that is just greater than 70–90% of the rainstorms (Joint Task Force 1998). Using the 90th percentile as the guideline, the storage volumes shown in Table 4 would be the BMP design volume for the eight cities listed. Table 5, taken from Roesner (1999), shows these design storms and their frequency of exceedance (or overflow frequency). Swales, infiltration basins, and extended detention facilities would be sized to accommodate these flows. Because the vol-

TABLE 4. Unit Storage Volume to Achieve 90% Capture of Annual Runoff Volume

City	Rainfall/Runoff Characteristics: Annual rainfall (mm)	Rainfall/Runoff Characteristics: Runoff coefficient	Storage volume required for 90% capture of annual runoff (mm)
Tucson, Ariz.	295	0.50	9
Butte, Mont.	371	0.44	5
San Francisco	490	0.65	23
Edinburgh, Scotland	700	0.43	12
Chattanooga, Tenn.	750	0.63	15
Detroit	889	0.47	7
Cincinnati	1,013	0.50	12
Orlando, Fla.	1,270	0.35	15

TABLE 5. Design Storm for 90 Percent Capture of Runoff

City	Overflow frequency (times/year)	Design storm (return interval)
Tucson, Ariz.	3	4 month
Butte, Mont.	6	2 month
San Francisco	4	3 month
Edinburgh, Scotland	4	3 month
Chattanooga, Tenn.	10	1.2 month
Detroit	12	1 month
Cincinnati	8	1.5 month
Orlando, Fla.	4	3 month

umes are small, it is often possible to retrofit existing regional flood control detention basins with small, low-level outlets thus providing extended detention basins for treatment of these small storms.

Effect of BMP Design on Flow Frequency Curve

The small runoff volume controlled by BMPs means that for storms larger than the design storm, the BMP will capture the first flush, thereby attenuating the initial portion of the runoff hydrograph. But once that volume is exceeded, the remainder of the flow is unregulated until the outflow control for the drainage detention basin begins to take effect. If the drainage outlet is designed for control of the 10-year storm, and the BMP design volume is for a 2-month storm, then approximately six times per year the flow peak will pass through the facility essentially unaffected. The magnitude of that peak will be somewhere between the 2-month postdevelopment flow peak and the 10-year predevelopment flow peak. The net effect of the BMPs and drainage detention basins on the flow frequency curve is illustrated in Fig. 6. As Fig. 6 shows, a significant portion of the flow frequency curve is still unregulated with this design protocol. It is this uncontrolled section of the flow frequency curve that the writers believe causes stream reaches downstream from BMPs to continue to exhibit habitat degradation and reduced biological indices.

Correcting the Problem

Many investigators in the scientific community have looked for a relationship between urban development and the ecologic health (or condition) of the receiving stream. The currently popular relationship to explore is percent impervious versus biological assessment indices as illustrated in Fig. 7 taken from Maxted and Shaver (1997).

Investigators then use these plots to draw conclusions about impacts of urbanization on ecologic integrity. This type of analysis has lead to the popular myth that the gross percent impervious of urban development must be limited to 12–15% in order to preserve stream biological integrity. But this type of graph does not take into account the moderating effects that changes in drainage system design can have on the hydrologic characteristics of the runoff. For example, the reduction of directly connected impervious area and inclusion of infiltration devices—such as infiltration basins that are widely used in Central Florida—or underdrained sand filtration basins that are used in Austin, Tex., and San Antonio, will have a significant effect on the flow frequency curve. By integrating the design of storage and outlet controls for flood control and BMPs it is possible to better control wet weather discharges to receiving waters over the entire range of flows that the facility experiences.

But it is not effective or realistic to seek one-size-fits-all prescriptions of land use controls or watershed controls for ecologic protection of urban streams. This approach fails to recognize the fundamental causes of channel instability and aquatic ecosystem degradation. Streams adjust to the water and

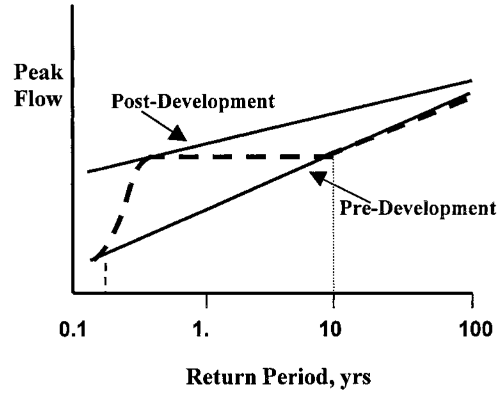

FIG. 6. Effect of Detention Storage and BMPs on Postdevelopment Peak Flow Frequency Curve

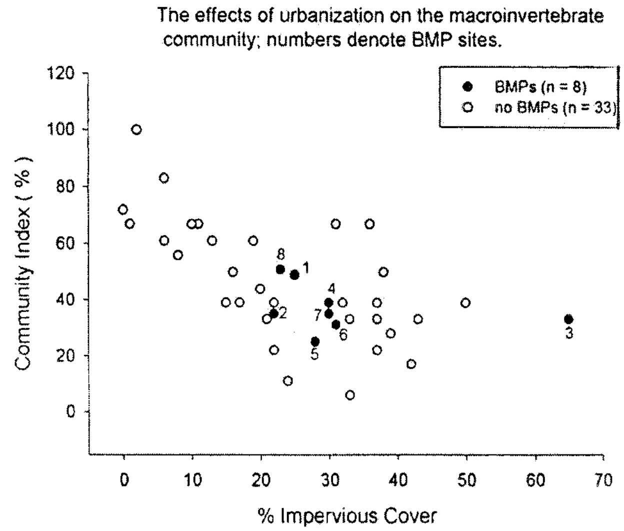

FIG. 7. Effect of Urbanization on Macroinvertebrate Community (Maxted and Shaver 1997)

sediment supplied to them by widely varied land use scenarios, each with unique runoff and sediment conveyance characteristics. Accordingly, stream protection and rehabilitation goals must be defined and based on general physical principles (Wilcock 1997). Managers must ask the following question: Given the potential flows of sediment and water out of the watershed, what are our options for achieving desired social and biological endpoints?

The writers believe that a two-step approach is required to link biological indices to watershed parameters:

1. Develop a relationship between stream geomorphologic characteristics and biologic indicators.
2. Develop a relationship between watershed hydrogeometric parameters and stream geomorphologic parameters.

Once this is accomplished, it will be possible to design holistic runoff control facilities into an urban development so that the community is afforded both protection from flooding and maintenance of a sustainable ecosystem in the urban stream.

TOWARD HOLISTIC DESIGN OF URBAN DRAINAGE SYSTEMS

Having come to the aforementioned conclusion, the United States currently finds itself in a dilemma with respect to protecting aquatic environments from the hydrologic changes that occur as the result of urban development. A basic problem is that local agencies are responsible for drainage and flood controls; and their mandates, with few exceptions, do not include protection of aquatic ecosystems. Thus, design criteria for urban drainage systems are centered around drainage and flood protection for the urban area with little or no account being taken of the impacts of that drainage on the ecologic environment to which that water is discharged.

Congress, in Section 401p of the Clean Water Act, tried to address the ecologic problem by requiring that pollutants in urban runoff be removed to the ''maximum extent practicable,'' but as the writers have illustrated in this paper, these best management practices, which are designed as treatment devices not as flow regulating devices, do not provide the degree of flow control needed to protect the aquatic environment.

More recent policy proposals for restoring the water quality of U.S. streams and rivers will also be largely ineffective and unsustainable in the long term unless policy makers recognize that biological health is related more to the geomorphic changes associated with land use conversion than the quality of the runoff. The Clinton Administration's Clean Water Initiative includes proposals for expanding wetland and riparian area restoration and controls on non–point-source pollution. The ecologic effectiveness of these efforts hinges on our ability to proactively manage the cumulative effects of wet weather flows on geomorphic processes and aquatic ecosystems. As stated in the preceding paragraph, storm-water controls may reduce pollutant delivery from source areas, but they still allow severe destabilization of streams and destruction of aquatic life. Riparian areas may be restored or protected, but eventually erosive processes linked to urbanization or some other land use change will undermine them. Streams may be only temporarily ''restored'' by adjusting channel form to a reference condition that is assumed to be stable under current hydrologic conditions. As land uses inevitably change, efforts such as riparian area and channel restoration will be sustainable only if they are outgrowths of a watershed strategy at the temporal scale of decades for managing fluxes of sediment and water for channel stability and aquatic ecosystem integrity.

Another issue is that the regulation of altered runoff and sedimentation processes during land use conversion usually occurs on an ad hoc basis, without regional planning and consideration of geomorphic processes (McCuen 1989; Urbonas and Stahre 1993). Storm-water management programs in most states and municipalities require site-by-site implementation of BMP facilities in developing areas using common design criteria because approach is the easiest to enforce administratively. However, such an approach does not account for increases in the frequency and duration of erosive forces and boundary material characteristics in the individual channels receiving the runoff. Thus, neither the flows that transport the most sediment, nor the duration of any flow, are maintained at predevelopment levels (Booth 1990). As a result, the sediment transport potential of post-development flows may be several times that of the pre-development conditions, despite the installation of upstream stormwater management facilities (see Hollis 1975; McCuen and Moglen 1988; Booth 1990; MacRae 1991, 1993, 1997). Effective mitigation of channel erosion hazards and aquatic ecosystem impacts necessitates the application of geomorphic principles in improving storm-water controls (Booth 1990; MacRae 1997).

The time is right to bring together the urban hydrology and environmental effects communities to develop guidance for improved storm-water management on urban watersheds. This guidance includes receiving water ecosystem impacts as well as drainage and flood control. USEPA, state water quality regulators, and an increasing number local storm drainage agencies have become aware of the importance of flow management for aquatic ecosystem protection, but they lack guidelines for design of such systems. Heaney et al. (1999) recognized this fact in a recent article on research needs in urban wet weather flows. But it is extremely important that the research be pragmatic and have its focus on developing pilot/demonstration studies that will lead to design guidance that municipalities can use to design new systems, or design improvements to existing systems that will not only protect the health and welfare of the citizenry that it serves, but will provide protection of the aquatic ecosystems that receive the wet weather discharges from these urbanized sites.

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