GUIDANCE DOCUMENT

DEVELOPMENT OF A DILUTION-ATTENUATION FACTOR FOR THE IMPACT TO GROUND WATER PATHWAY

Version 2.0 – November 2013

New Jersey Department of Environmental Protection
Trenton, New Jersey

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I. Introduction

As infiltrating precipitation containing leached contaminant recharges an aquifer at the water table, it mixes with ground water, reducing the leachate contaminant concentration. The amount of dilution and the resulting ground water contaminant concentration can be calculated with a dilution-attenuation factor (*DAF*)

The *DAF* is described in the USEPA Soil Screening Level (USEPA SSL) document (USEPA 1996). The *DAF* is used in the various options for calculating impact to ground water soil remediation standards, including calculation of the Leachate Criterion.

The *DAF* is calculated using Equation 1 below. In addition to aquifer and site physical parameters, this equation requires a value for the mixing zone depth in the aquifer, which is calculated using Equation 2. These two equations are taken from USEPA SSL guidance document.

Equation for calculating the dilution-attenuation factor (*DAF*):

$$DAF = 1 + \frac{Kid}{IL}$$ **Equation 1**

where

i = gradient (m/m)
d = mixing zone depth (m), calculated below (Equation 2)
I = infiltration rate (m/yr)
L = length of area of concern parallel to ground water flow (m)
K = aquifer hydraulic conductivity (m/yr)

Equation for calculating the aquifer mixing zone depth, d:

$$d = (0.0112\,L^2)^{0.5} + d_a\left\{1 - \exp\left[(-LI)/(Kid_a)\right]\right\}$$ **Equation 2**

where

d_a = aquifer thickness (m)

Dilution of the contaminant due to transport through the unsaturated soil zone is ignored, because soil contamination is assumed to be immediately adjacent to the water table. Volatilization and chemical degradation are also not considered, because contaminant contact with the ground water is assumed to occur immediately.

In 2012, the Department established a Committee to review and update guidance documents for developing site-specific impact to groundwater soil remediation standards. The Committee included Stakeholders and NJDEP staff. This guidance represents the work of the Committee and it supersedes any previous Department guidance issued on this topic. The following people were on the Committee that prepared this document:

Dr. Swati Toppin, Chair	NJDEP
George Blyskun	NJDEP
Ann Charles	NJDEP
Dr. Barry Frasco	NJDEP
MaryAnne Kuserk	NJDEP
Dr. Paul Sanders	NJDEP
Matthew Turner	NJDEP
Michael Gonshor	Roux Associates, Inc.
Stephen Posten	AMEC Environment and Infrastructure

II. Default *DAF* Value

A default *DAF* of 20 for use with New Jersey remediation cases has been determined. The basis for this value is described in Appendix A.

III. Site-Specific Modification of Default Dilution-Attenuation Factor (*DAF*)

Several parameters that are used in the calculation of the *DAF* may be adjusted on a site-specific basis. A site-specific dilution-attenuation factor may then be calculated and used to determine a site-specific LC value and/or a site-specific impact to groundwater soil cleanup standard. In particular, higher ground water flow rates than those assumed for calculation of the default *DAF* will result in a higher *DAF* (Appendix B), and may significantly increase the soil cleanup standard.

When determining a site-specific *DAF* value, the length of the area of concern parallel to ground water flow, *L*, must be adjusted in all cases to reflect actual conditions. In addition, the calculated mixing zone depth cannot be greater than the aquifer thickness (see below). The following parameters may be modified in the *DAF* equation:

A. Length, *L*

The *DAF* is only affected by the length of the area of concern (*L*) when it becomes large enough to cause the calculated mixing zone depth to become greater than the actual thickness of the aquifer (see Appendix B). Use the following procedure to calculate a site-specific *DAF* when adjusting the value of *L*:

(1) Measure the length of the area of concern parallel to ground water flow.

(2) Use the length to develop a site-specific mixing zone depth using Equation 2. If the calculated mixing zone depth is greater than the aquifer thickness (see below), set the mixing zone depth equal to the aquifer thickness.

(3) Substitute the site-specific values for the mixing zone depth and *L* into the equation for the *DAF* (Equation 1).

B. Infiltration Rate, *I*

The default infiltration rate is 11 inches/year, calculated for sandy loam soil, as described in the Basis and Background Document for the Inhalation Soil Remediation Standards (NJDEP 2008). However, if site-specific infiltration rate data (i.e., ground water recharge data) are available or determined by site investigation, this information may be used. At this time, site-specific adjustment of infiltration rates is allowed only after consultation with the Department. The Department will not allow impermeable cover to be considered in the development of the infiltration rate. For example, paving, which may result in a reduced infiltration rate, would not be allowed to modify the infiltration rate.

C. Ground Water Velocity Parameters (Hydraulic conductivity, *K* and Gradient, *i*)

Because *K* and *i* are closely linked parameters affecting ground water velocity they must be adjusted together. The *DAF* is approximately linear with respect to these two parameters. Use the following procedure:

(1) Determine *K* and *i* from field measurements pursuant to the Department's Ground Water Technical Guidance (NJDEP 2012).

(2) Measure the length (*L*) of the area of concern parallel to the ground water flow.

(3) Substitute *K*, *i*, and *L* into the mixing zone equation (Equation 2) to determine a site-specific mixing zone depth. If the calculated aquifer mixing zone depth is greater than the aquifer thickness (see below), set the mixing zone depth equal to the aquifer thickness.

(4) Substitute the site-specific values for *K*, *i*, *L* and the mixing zone depth into the equation for the dilution-attenuation factor (Equation 1) to calculate a site-specific *DAF*.

D. Aquifer Thickness, d_a

This parameter only affects the *DAF* if the calculated mixing zone depth is greater than the aquifer thickness. Use the following procedure to adjust the aquifer thickness and calculate a site-specific *DAF*:

(1) Aquifer thickness shall be measured in the field using appropriate methods or shall be determined using available data from the New Jersey Geological Survey or the United States Geological Survey when appropriate (e.g., assuming aquifer thickness determinations by the

NJGS or USGS are at or in close proximity to the subject site). In cases where aquifer thicknesses are large, it only needs to be demonstrated that the aquifer thickness is greater than the calculated mixing zone depth.

(2) Measure the length (*L*) of the area of concern parallel to ground water flow.

(3) Use the site-specific aquifer thickness and the actual length of the area of concern in the mixing zone depth equation (Equation 2) to calculate a site-specific mixing zone depth. If the calculated aquifer mixing zone depth is greater than the aquifer thickness, set the mixing zone depth equal to the aquifer thickness.

(4) Use the calculated site-specific mixing zone depth, and the site-specific value for *L* in the *DAF* equation to calculate a site specific *DAF* (Equation 1).

IV. Submission Requirements

In order for the Department to efficiently review proposed site-specific soil impact to ground water soil remediation standards, it is recommended that the person responsible for conducting the remediation use the spreadsheet provided by the Department at

http://www.nj.gov/dep/srp/guidance/rs/daf_calc.xls.

Submit a copy of the spreadsheet to the Department.

Documentation for all input parameters used to determine the site-specific *DAF* value should be submitted to the Department.

APPENDIX A

Determination of the Default Dilution-Attenuation Factor (*DAF*)

To determine a default Dilution-Attenuation Factor (*DAF*) for New Jersey, default values for the variables in Equations 1 and 2 in this guidance document are necessary. The development of each of these values is discussed below. A comparison with the default values used by the USEPA in its Soil Screening Guidance Document (USEPA 1996) is also included.

Input Parameters for the *DAF* Equation

Source (Area of Concern) Length Parallel to Ground Water Flow (*L*)

USEPA default value: 45 m (148 feet)
NJDEP default value: 30 m (100 feet)

This parameter is set equal to the length of the Area of Concern (AOC) parallel to ground water flow and it is used in calculating the *DAF*. The Department's value results in higher remediation criteria than if USEPA's value was used. The 100 feet source length was judged to be larger than most Areas of Concern in New Jersey, and therefore adequately protective. This is also approximately equal to the length of a high density residential lot size (¼ acre). The source length affects the *DAF* and remediation standard only if it results in a calculated mixing zone thickness that is larger than the aquifer thickness (see Appendix B).

Thickness of Affected Aquifer (d_a)

USEPA: Monte Carlo Distribution
NJDEP: 3.5 m (11.5 ft)

The aquifer thickness is used in calculating the aquifer mixing zone depth, which in turn is used in calculating the *DAF*. For the default site size, the calculated *DAF* is independent of the aquifer thickness if it is 3.4 m or greater. Since 3.5 m represents a relatively thin aquifer (11.5 ft), this value was considered to be adequately protective and used as the default value.

Hydraulic conductivity (*K*) and gradient (*i*)

USEPA: Monte Carlo Distribution
NJDEP: *K*: 142 ft/day
i: 0.003

Representative values for the hydraulic gradient (*i*) and hydraulic conductivity (*K*) for the Kirkwood-Cohansey aquifer were used to determine a default *DAF* value for New Jersey. This 3,069 square mile aquifer is relatively shallow, lies underneath soils with considerable sand content, and often exhibits low flow rates due to generally flat terrain. It comprises almost 75% of the N.J. Coastal Plain, and being a surficial water table aquifer, is vulnerable to contamination.

Many water resource studies have been completed for this aquifer system because it is widespread and supplies potable water to many communities. Therefore, a significant amount of hydrogeologic data is available. For these reasons, it was selected as an appropriate aquifer for determining representative *K* and *i* values for New Jersey.

A statistical analysis of data for the Kirkwood-Cohansey aquifer was conducted. The hydraulic gradient (*i*) was calculated by measuring the potentiometric surface at 235 locations on maps of water table elevations in eight watershed basins (listed in Appendix C), and median, mean, geometric mean and mode values were calculated. Statistical analysis typically requires at least 30 data points, while 200 are considered sufficient for rigorous applications. The analysis indicated a tight grouping in the measurements over the entire Kirkwood-Cohansey system, leading to confidence in the results. The geometric mean is a "smoothing mean". Its value was close to both the median and mean values and is evidence of the tight grouping in the measurements. The statistics for the Kirkwood-Cohansey gradient were as follows:

Mean	0.004
Median	0.003
Geometric Mean	0.003
Mode	0.002
Std. Deviation	0.002
Coeff. of Variation	0.67

Investigators report a geologic formation dip of 10-60 feet/mile (0.002-0.011) for the N.J. Coastal Plain (Volwinkel and Foster, 1981). On the scale of the Coastal Plain, one can reasonably assume this dip mirrors the hydraulic gradient in a water table aquifer; so the calculated values above appear compatible with this range. A gradient of 0.003 was selected as appropriate for this aquifer.

To determine a representative hydraulic conductivity for the Kirkwood-Cohansey aquifer, data was collected from the results of 67 aquifer stress tests. Thirty-three were compiled by the New Jersey Geological Survey (NJGS) (Canace and Sugarman, 2009), 13 were from the U. S. Geological Survey (USGS) (Martin, 1990); and 23 were taken from the eight individual watershed basins reported on the water table maps listed below. The NJGS and USGS reported median hydraulic conductivities for the compiled tests; individual test values were not reported. The basin tests were reported individually, but detailed statistical analysis was not attempted because less than 30 test results were available. Results were checked for redundancy; all 67 tests from these sources are unique. Results are as follows:

- 46 NJGS and USGS Tests Median (weighted) hydraulic conductivity: 138 ft./day.
- 21 Basin Tests from the aquifer maps: Median hydraulic conductivity: 150 ft./day

An overall weighted median value of 142 ft./day was calculated from the two values above, and is consistent with the surficial Kirkwood-Cohansey aquifer material type (medium to coarse sand) and high well yields.

Additional considerations regarding New Jersey K and i values

Hydraulic gradients were measured in eight major watersheds of the eleven for the Kirkwood-Cohansey aquifer in the Coastal Plain. Water resource investigations have not been completed for the remaining three, and potentiometric data is therefore unavailable for analysis.

Regarding other aquifers in the Coastal Plain, unconsolidated sediments make up the remainder of the surficial water table aquifer in the westernmost outcrop areas of the inner Coastal Plain. Hydraulic data for the underlying aquifers that outcrop in this area (between the Kirkwood-Cohansey and the Delaware River) were too few for reliable estimates. However, these outcrop areas are limited in geographic extent and were judged to be similar to the Kirkwood-Cohansey. Estimates of infiltration rates as an indicator of hydraulic conductivity in these surficial aquifers, as well as their material character, suggests that the Kirkwood-Cohansey surficial water aquifer is representative of these other aquifers for Default *DAF* purposes. Local variations are likely, but also occur in the Kirkwood-Cohansey.

While these *K* and *i* values are based on the coastal plain of New Jersey, the resulting *DAF* calculated using these values was judged to be representative for the entire state (see Appendix D and section below: "Discussion of Default Dilution-Attenuation Factor").

The remediation standard is approximately linear with respect to hydraulic conductivity and the aquifer gradient (Appendix B).

<u>Infiltration Rate (*I*)</u>

USEPA: Monte Carlo Distribution
NJDEP: 0.28 meters/yr (11 inches/yr)

The infiltration rate corresponds to the rate of recharge of precipitation to the ground water. The infiltration rate is an input parameter for calculating the *DAF*. The infiltration rate was calculated for a default sandy loam soil and a New Jersey climate using a model from the New Jersey Geological Survey. See the Basis and Background Document for the Inhalation Soil Remediation Standards (NJDEP 2008) for further details.

<u>Mixing Zone Depth (*d*)</u>

USEPA: Monte Carlo Distribution
NJDEP: 3.4 m (11 ft)

The mixing zone depth corresponds to the depth to which the contaminant is diluted in ground water. It is calculated from the mixing zone depth equation (Equation 2) using several other field parameters. The mixing zone depth is then used in the *DAF* Equation (Equation 1). Using the default values for all of the parameters that are used in this equation, the default mixing zone depth is calculated to be 11 feet, which is slightly less than the default aquifer thickness. The parameter remains at this value under the default scenario even if the aquifer thickness is increased. Sensitivity analysis was not conducted for this parameter because its dependent parameters are incorporated in the sensitivity analysis for the *DAF* equation (Appendix B).

Discussion of the Default Dilution-Attenuation Factor

Substituting the parameters discussed above into Equations 1 and 2, a default dilution-attenuation factor of 20 was calculated.

While most of the parameters for the *DAF* were based on a statewide representative values, the *K* and *i* values were based on an assessment of the coastal plain of New Jersey. The remainder of New Jersey has more complex geology. Unlike the New Jersey coastal plain, where aquifer properties viewed over a large scale are less variable and the hydraulic setting more uniform, northern New Jersey overburden aquifers are heterogeneous. Successive glaciations have reworked and re-deposited mixtures of clay, sand, silt, and glacial lake sediments. Accordingly, hydraulic properties can vary significantly over short distances. Furthermore, few regional studies have been completed in the northern part of the state, so data are limited relative to that available for the coastal plain. For this reason, representative *K* and *i* values could not be determined for the northern part of the state.

Since statewide *K* and *i* values are not used to calculate the default *DA*F, it was of interest to examine other information that was available regarding dilution-attenuation factors that may apply to the northern part of the state. The NJDEP examined USEPA-calculated *DAF* values for the particular geologic materials found in northern New Jersey. In Appendix F (HGDB database, National Average) of the USEPA Soil Screening Guidance (USEPA 1996), the USEPA compiled 208 values for the *DAF* for its sites throughout many regions of the country. Seventeen *DAF* values were chosen that best represented northern NJ geology (glaciated and upland regions) and the default size of the area of concern (0.5 acre source area). Statistics were applied to the selected values for *DAF* and yielded the following results:

- Arithmetic Mean: 36.5
- Geometric Mean: 17.8
- Median: 21
- Standard Deviation: 45.9
- Coefficient of Variation: 1.26

While this assessment is not as rigorous or quantitative as that conducted for the southern part of the state, the geometric mean and median *DAF* values shown above for northern New Jersey are similar to the default *DAF* of 20 determined using default *K* and *i* values for the coastal plain. Therefore, it was judged that a *DAF* of 20 was suitable as a default dilution-attenuation factor for the entire state.

Additional discussion regarding the USEPA *DAF* values in the USEPA Soil Screening Guidance Document and their relationship to New Jersey's default *DAF* is presented in Appendix D.

APPENDIX B

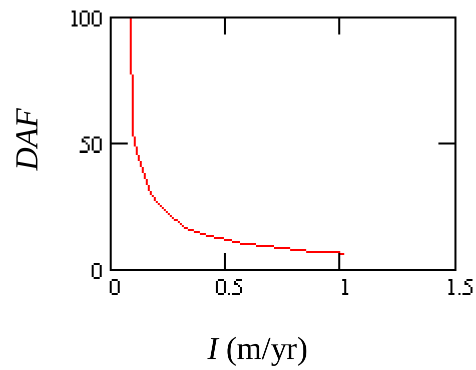
Sensitivity of the *DAF* to its Constituent Parameters

For this analysis, one variable was modified at a time, while the other environmental parameter values were set at default New Jersey values (see the Basis and Background Document for the Inhalation Soil Remediation Standards for default values (NJDEP 2008)).

1. Sensitivity of dilution-attenuation Factor (*DAF*) to infiltration rate (*I*).

DAF sensitivity is inversely proportional to infiltration rate, *I*. Mixing zone depth not constrained by aquifer thickness.

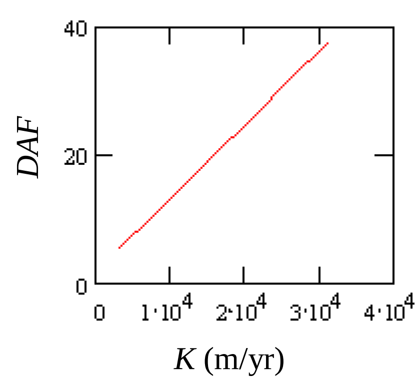
I (m/yr)	*DAF*
0.025	198
0.102	51
0.178	30
0.254	22
0.33	17
0.406	14
0.483	12
0.559	11
0.635	9.8
0.711	8.9
0.787	8.3
0.864	7.7
0.94	7.2
1.016	6.8



2. Sensitivity of dilution-attenuation factor (*DAF*) to hydraulic conductivity (*K*).

DAF sensitivity is slightly less than linear with respect to conductivity, K. Mixing zone depth not constrained by aquifer thickness in this calculation.

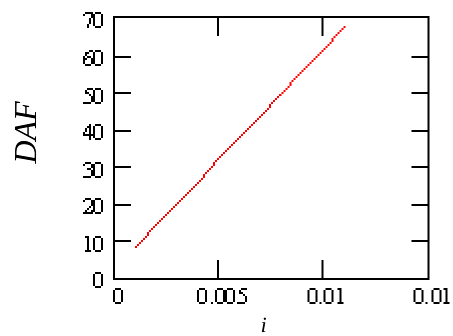
K (m/yr)	*DAF*
3155	6
6311	9
9467	13
12622	16
15778	20
18934	23
22089	27
25245	30
28401	34
31556	38



3. Sensitivity of dilution-attenuation factor (*DAF*) to gradient (*i*).

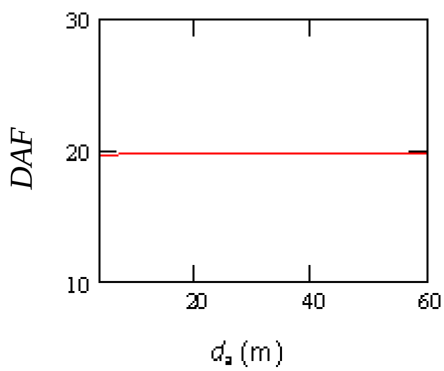
DAF sensitivity is slightly less than linear with respect to gradient, *i*. Mixing zone depth not constrained by aquifer thickness in this calculation.

i	*DAF*
0.001	8
0.002	14
0.003	20
0.004	26
0.005	32
0.006	38
0.007	44
0.008	50
0.009	56
0.01	62
0.011	68



4. Sensitivity of dilution-attenuation factor (*DAF*) to aquifer thickness (d_a).

When aquifer thickness is 3.4 m or greater, the aquifer thickness has no effect on the *DAF*.



5. Effect of size of area of concern on the *DAF*.

DAF as a function of the size of the area of concern (mg/kg)			
	Length of Site		
	Parallel to GW flow (m)		
	15.2	*30.5*	*152*
Aquifer thickness = 3.5 m	20	20	5
Aquifer thickness = 15.2 m	20	20	18

Under default conditions, a lower *DAF* results when the site length becomes large. However, this effect is reduced when the aquifer thickness increases.

APPENDIX C

Maps of Water Table Elevation and Hydraulic Conductivity Used in the Assessment of the Kirkwood-Cohansey Aquifer

Rancocas, Crosswicks, Assunpink, Blacks, and Crafts Creek Basins (43 gradient measurements and 1 aquifer test) (Watt et al. 2003)

Maurice and Cohansey River Basins (37 gradient measurements and 10 aquifer tests) (Charles et al., 2001)

Salem River and Raccoon, Oldman's, Alloway, and Stow Creek Basins (24 gradient measurements and 10 aquifer tests) (Johnson and Charles, 1997)

Toms River, Metedeconk River and Kettle Creek Basins (37 gradient measurements and 3 aquifer tests) (Watt et al. 1994)

Forked River and Cedar, Oyster, Mill, Westecunk, and Tuckerton Creek Basins and Adjacent Basins (11 gradient measurements and 2 aquifer tests) (Gordon, 2004).

Upper Maurice River Basin and Adjacent Areas (18 gradient measurements and 5 aquifer tests) (Lacombe and Rosman, 1995)

Mullica River Basin (47 gradient measurements and 6 aquifer tests) (Johnson and Watt, 1996).

Great Egg Harbor Basin (18 gradient measurements and 10 aquifer tests) (Watt and Johnson, 1992).

APPENDIX D

Discussion of USEPA Assessment of Dilution-Attenuation Factors

The USEPA conducted a nationwide assessment of dilution-attenuation Factors (*DAF*s) in its Soil Screening Guidance Document (USEPA 1996). Nationally, *DAF* values for a half-acre site were found to range from one to several thousand. To derive a default *DAF* value, the USEPA used a "weight of evidence" approach to derive its default attenuation factor of 20. This was based on two studies where attenuation factors were estimated or calculated.

In the first study, USEPA's Composite Model for Leachate Migration with Transformation Products (EPACMTP) model was used to derive *DAF* values by running the model in the Monte Carlo mode. *DAF* distributions were generated using expected variations in the input parameters that are used in its calculation. While this approach has its advantages, it resulted in a nationwide distribution of *DAF* values that were inappropriate for New Jersey use, based on policy considerations. *DAF* values were calculated at the location of a receptor well, which was varied in its location and was often outside the main body of the contaminated groundwater plume. If the well was outside the plume, a high *DAF* was calculated. This is incompatible with New Jersey policy, since the probable location of a receptor well is not considered in the New Jersey Ground Water Quality Standards. All groundwater is to be protected for potential potable uses. Therefore, the *DAF* should be calculated within the plume itself. Additionally, the USEPA assumed a variable distance between the down gradient edge of the source and the receptor well. This is also incompatible with the Ground Water Quality Standards (N.J.A.C. 7:9C), which require compliance at the down gradient edge of the source.

In the second study, the USEPA used data from two large surveys of hydrogeological site investigations, and calculated *DAF* values using the *DAF* Equations presented above. The two surveys were the American Petroleum Institute's (API's) hydrogeologic database (HGDB) and USEPA's database of conditions at Superfund sites contaminated with DNAPL (USEPA 1996). Between these two databases, a total of 300 *DAF* calculations were made. The sites are classified according to hydrologic region in the United States. Three of these regions, the Northeast and Superior Uplands, the Glaciated Central Region and the Atlantic and Gulf Coast, are appropriate for New Jersey. The use of the HGDB database to evaluate northern New Jersey *DAF* values was discussed above (Appendix A). For the Atlantic Coast region, the HGDB database contained 15 values reported for the Atlantic Coast region for unconsolidated and semi-consolidated shallow surface aquifers (0.5 acre site size). Data were highly skewed, with a median *DAF* of 3 and mean of 30. The DNAPL database yielded 50 sites in the Uplands region and 12 sites in the Atlantic Coast region with median *DAF* values (0.5 acre site size) of 22 and 20, respectively. (Glaciated Region data was inadequate for assessment.) While these median values support the NJDEP default *DAF* of 20, none of the sites in the database were in New Jersey, and less details were available regarding the hydrogeologic settings than for the HGDB database.

The NJDEP study of the Kirkwood-Cohansey aquifer provides the best data regarding dilution-attenuation factors values in New Jersey, and led to selection of a default *DAF* of 20. The available USEPA data discussed above, while not specific to New Jersey, and not as quantitatively rigorous, also lend support to this default *DAF* value.

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