UNIVERSIDAD NACIONAL DE COLOMBIA
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Identification of resilience factors, variables and indicators for sustainable management of urban drainage systems

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Received: June 14th, 2016. Received in revised form: July 19th, 2017. Accepted: September 30th, 2017

Abstract
Water management systems in general and urban drainage systems (UDS) in particular should be designed to ensure not only the provision of public service but also their sustainability and resilience. This paper performed an analysis and assessment to identify the factors, variables and indicators of resilience for sustainable UDS management by using an information management tool for scientific subjects. As a result of this analysis, four water resource resilience factors were identified: *i.* Flexibility; *ii.* Resourcefulness; *iii.* Redundancy; and *iv.* Robustness. In addition, six UDS resilience variables were identified: *i.* Recovery capacity; *ii.* Response capacity; *iii.* Amplitude; *iv.* Absorption capacity; *v.* Resistance capacity; and *vi.* Response curve. Corresponding indicators were proposed to quantify these variables. The identified elements contribute to the development of integrated frameworks to assess UDS resilience.

Keywords: urban drainage; management; resilience; sustainability.

Identificación de factores, variables e indicadores de resiliencia para la gestión sostenible de sistemas de drenaje urbano

Resumen
La gestión del agua en general y de los sistemas de drenaje urbano (SDU) en particular, debe ser concebida no solo para asegurar la prestación de un servicio público, sino también para garantizar su sostenibilidad y resiliencia. En el presente artículo se presenta un análisis y reflexión que permitió identificar los factores, variables e indicadores de resiliencia para la gestión sostenible de SDU, usando herramientas de gestión de información de temas científicos. Como resultado de este análisis, se identificaron cuatro factores de resiliencia de recursos hídricos: *i.* Flexibilidad; *ii.* Recursividad; *iii.* Redundancia; y *iv.* Robustez y seis variables de resiliencia de SDU: *i.* Capacidad de recuperación; *ii.* Capacidad de respuesta; *iii.* Amplitud; *iv.* Capacidad de absorción; *v.* Capacidad de resistencia; y *vi.* Curva de respuesta. Para cuantificar estas variables, se proponen sus correspondientes indicadores. Los elementos identificados contribuyen al desarrollo de modelos integrales de evaluación de la resiliencia en SDU.

Palabras clave: drenaje urbano; gestión; resiliencia; sostenibilidad.

1. Introduction

Cities must be able to face 21st century threats such as rapid urbanization, population growth, climate change and variability, energy restrictions and increased environmental regulation [1]. Novotny [2] noted that urban water management becomes unsustainable in the face of extreme events such as floods or droughts, which are expected to increase in frequency as a result of global warming.

Accordingly, there is a need to consider resilience in the planning, design and construction of urban infrastructure as embodied in the Sustainable Development Goals (SDGs) formulated by the UN for 2016-2030 [3].

Urban infrastructure elements such as urban drainage systems (UDS) are vulnerable to these aforementioned threats; therefore, design and operational processes must account for system weaknesses, operational failures, and the incorrect interpretation and use of information to ensure

How to cite: Blanco-Londoño, S.A., Torres-Lozada, P. and Galvis-Castaño, A., Identification of resilience factors, variables and indicators for sustainable management of urban drainage systems DYNA, 84(203), pp. 126-133, December, 2017.

sustainability [4].

Thus, the concept of resilience comes to the fore when seeking to improve the sustainability of urban infrastructure in the future.

Given the importance of this concept in UDS management, we will discuss the evolution of resilience, going from the narrowest sense of the word to a broader interpretation, while examining how it has been addressed as it relates to UDS management.

1.1. Evolution of the concept of resilience

The concept of resilience arose from the field of ecology in the 1960s through studies of predator-prey population interactions and their functional responses as they relate to the theory of ecological stability.

Holling [5] proposed that "*resilience determines the persistence of relationships within a system and is a measure of the capacity of these systems to absorb changes in variables of state, variables of conduction and parameters, and being able to persist*". Many years later, Holling [6] classified resilience into "*engineering resilience*" and "*ecological resilience*" to emphasize the differences between efficiency, stability and predictability on the one hand and persistence, change and unpredictability on the other.

Engineering resilience is characterized by analysing return periods and efficiency by focusing on the recovery capacity of a system in the context of a stable equilibrium. Ecological resilience, in turn, emphasizes the instability that can "move" a system to another regimen of behaviour (also known as the "basin of attraction").

Based on these concepts, Holling [6] defined resilience as "*the magnitude of the disturbance that can be absorbed before the system redefines its functional structure, changing the variables and processes that control behaviour*". Resilience is characterized as the capacity to absorb changes, resist disturbances and maintain functions while focusing on the persistence and robustness of a system in the context of global stability.

Because these different interpretations of resilience were causing confusion, and by arguing that the resilience of a system must be considered in terms of the attributes that control the dynamics of a system. Walker *et al.* [7] added a third category: socio-ecological resilience, defined as "*the potential of a system to tolerate disturbances without collapsing towards a qualitatively different state, maintaining its structure and function, which involves its capacity to reorganize itself, following the changes driven by disturbances*".

Socio-ecological resilience is characterized by analysing the interactions between disturbances, reorganization, sustainability and development in a system and focusing on the capacity to adapt, transform, learn and innovate in a context of unstable equilibrium.

This concept modified existing views that considered systems to be stable by introducing a new perspective that considered the capacity of systems to adapt and change, thus increasing the probability of sustainable development in changing environments where the future is unpredictable.

Table 1.
Characteristics, perspectives and context of different resilience concepts.

Concept	Characteristics	Perspective	Context
Engineering resilience	Return period, efficiency	Recovery, stability	Surroundings of a stable equilibrium
Ecological or social resilience	Capacity to absorb, resist shocks, maintain functions	Persistence, robustness	Multiple equilibriums, stability landscapes
Socio-ecological resilience	Perturbation and reorganization, sustainability and development	Capacity to adapt, transform, learn, innovate	Integrated feedback of the system, dynamic interactions between scales

Source: Adapted from [11]

This broad category integrates resilience with socio-ecologic systems (SES), which integrate social and ecological systems, by focusing not only on the components of both systems but also on their interactions [7].

The SES concept incorporates ideas from fields related to adaptation, robustness and vulnerability by concerning itself with the dynamics and attributes involved in each of these terms, thus becoming broader in scope than any of these individual fields [8,9].

Within the domain of a social system lie subsystems such as culture, politics, the economy, and social organization (society itself); an ecological system domain hosts subsystems such as nature (a setting not created by man) and the environment (a setting created by man) [10].

Folke [11] defined socio-ecological resilience as "*an approach or way of thinking that presents a perspective to guide and organize thinking from a broader perspective, providing a valuable framework for the analysis of SES*". This places this field under exploratory research and rapid development, with political implications for sustainable development.

Table 1 synthesizes the major characteristics, perspectives and context of the three concepts of resilience we have identified.

1.2. Resilience for sustainable management of UDS

Different methodologies have been formulated to quantify the concept of resilience; Hosseini *et al.* [12] classified the procedure for evaluating resilience into qualitative and quantitative methodologies.

The qualitative methodologies include conceptual frameworks (they provide a notion of resilience but do not provide a quantitative value) and semi-quantitative indices (they involve the opinion of experts in their estimation), and the quantitative methodologies include general resilience metrics (they evaluate resilience in the performance of a system) and structural-based models (they evaluate resilience by components).

Based on this classification, Table 2 shows several studies that use the different methodologies to evaluate resilience.

Table 2.
Classification of different methodologies used to evaluate resilience.

Source	Qualitative: Conceptual frameworks	Qualitative: Semi-quantitative	Quantitative: General metrics	Quantitative: Structural based-models	Field of Study
[13]	✓				Socio-Ecological
[14]	✓				Socio-Ecological
[15]	✓				Urban water
[16]	✓				Urban water
[17]	✓				Urban drainage
[18]		✓			Water resources
[19]		✓			Socio-Ecological
[20]		✓			Water supply
[21]		✓			Water resources
[22]		✓			Water resources
[23]			✓		Water resources
[24]			✓		Water resources
[25]			✓		Water resources
[26]			✓		Water resources
[27]			✓		Water resources
[28]			✓		Water resources
[29]			✓		Water resources
[30]			✓		Water supply
[31]			✓		Water supply
[32]			✓		Urban drainage
[33]			✓		Urban drainage
[34]				✓	Urban drainage

Source: Created by author

Although different methodologies have been proposed to evaluate resilience, there are few studies that have focused on developing the appropriate methodologies to evaluate resilience in UDS [35,36], which makes the study of resilience in this field a novel topic of research for developing quantifiable indicators of resilience that can evaluate all the aspects involved in this concept [16].

To analyse resilience in UDS, conceptual frameworks [17], general resilience metrics [32,33] and structural-based models [34] have been proposed, the majority of which evaluate flood risk in UDS; only one addresses the problem of dragging pollutants [32].

Based on the conceptual perspective of resilience, these frameworks are primarily framed within the concept of engineering resilience. This provides an opportunity to develop new approaches that can evaluate resilience as it applies to UDS and ideally involve an SES from the point of view of socio-ecological resilience; this topic has not been previously addressed, even though there is a wide field of research to be developed.

As a result, this article presents an analysis and related impressions of applying the concept of resilience to the sustainable management of UDS by identifying the various factors, variables and indicators.

2. Methodology

The methodology for the management of scientific information proposed by Gómez *et al.* [37] was used to identify the variables and indicators of resilience for the sustainable management of UDS.

This methodology consists of four phases: *i. Definition of the problem; ii. Search for information; iii. Organization of the information;* and *iv. Analysis of the information*.

To define the problem, we began with the key concepts of sustainability, resilience and SES and their relationship with the sustainable management of UDS. The *Scopus* database was used to search for information by using keywords such as "sustainability", "resilience", "socio-ecological systems" and "urban drainage", in addition to keywords referring to important problems related to UDS such as "climate change", "flood risk" and "diffuse pollution". The period of observation extended from 1979 (when the concept of resilience initially appeared in engineering) until February of 2016.

The following search equations were used: *"Resilience AND Socio-Ecological Systems", "Resilience AND Sustainability OR Urban Drainage", "Resilience AND Urban Drainage", "Resilience AND Sustainability AND Climate Change", "Resilience AND Flood Risk", "Socio-Ecological Systems AND Sustainability", "Socio-Ecological Systems AND Climate Change", "Sustainability AND Urban Drainage", "Sustainability AND Climate Change OR Urban Drainage", "Sustainability AND Diffuse Pollution", "Sustainability AND Flood Risk", "Urban Drainage AND Climate Change", "Urban Drainage AND Diffuse Pollution"* and *"Urban Drainage AND Flood Risk"*.

The data mining program *RefViz* [38] was used to organize the information and select the most relevant articles; the program uses mathematical algorithms to group articles by topic based on the keywords. The results were used to create a concept map denominated as a galaxy in which each topic was grouped based on the frequency of the keywords. The organized information yielded 596 articles of interest forming 24 topic groups.

Once the information was organized, we selected documents and authors for review. After reading the abstracts and conclusions of those articles, an analysis was performed of the articles with the most important ideas and the most relevant aspects for the topic of this study. Once this was completed, were selected four of the 24 groups formed in the information search stage that were of most interest (groups G16, G17, G19 and G21); these included 122 articles. To make this articles selection, it was taken into account that resilience was a main keyword of the document.

The filtered documents were studied in more detail (i.e. it was made a scanning reading of each document) to select those that were relevant for this research (i.e. documents that include all or some factors for the evaluation of resilience in water resources). A total of 19 articles were used to carry out the analysis and comparison of the application of the resilience concept and to identify the common and relevant elements of resilience and the factors, variables and indicators for the sustainable management of UDS.

Fig. 1 shows the groups of interest regarding the topics consulted based on the previously described methodology.

3. Results and discussion

3.1. Resilience factors in water resource management

It was determined that resilience was impacted by four factors: *i.* Flexibility (capacity to change); *ii.* Resourcefulness

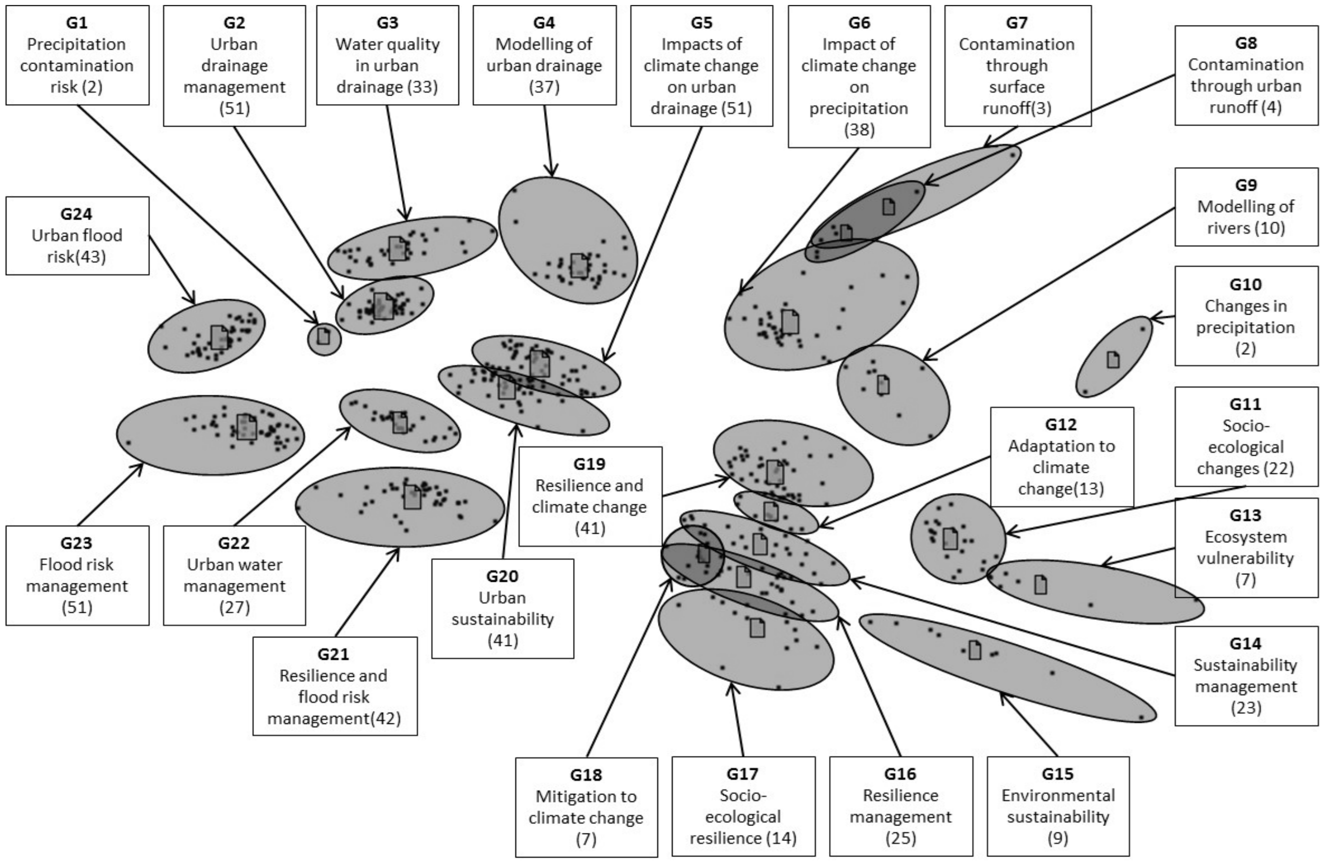

Figure 1. Interest groups in the consulted topics. Period 1979 – February 2016.
Source: Created by author

Table 3.
Characteristics of factors considered to evaluate resilience in the management of water resources.

Factor	Description	Adaptation strategies
Flexibility	Capacity to change, evolve and adopt alternative strategies (in the short or long term) in response to changing conditions; implies recognizing when it is not possible to return to the previous condition and searching for new solutions and strategies (evolution) [15,39].	Flexibility could be increased through the use of spatially distributed systems (decentralized) or modular systems or by providing storage capacity [16,41].
Resourcefulness	Capacity to visualize and act to identify problems, establish priorities and mobilize resources when faced by conditions that threaten to change an element of the system [15,40].	Resourcefulness can be increased by mobilizing human resources and assets (financial, physical, social, environmental and technological resources and information), supporting priorities and establishing goals [15,28].
Redundancy	Availability of elements or systems that can be substituted or activated when interruptions occur due to disturbances, allowing vital functions of a system to continue while the redundant elements assume new functions [33,40].	Redundancy could be improved through the addition of multiple elements or components that provide similar functions to minimize the propagation of failures through the system or operations that make it possible to divert exceptional load conditions to alternative parts of the system [41].
Robustness	Capacity of systems to resist a particular level of stress without suffering unacceptable degradation or loss of functions [40].	Robustness requires the exploration of the response and recovery of the system over a range of disturbance magnitudes; it also includes analysis of uncertainty caused by the variability of data and randomness of system parameters [42].

Source: Created by author

(capacity to mobilize resources); *iii.* Redundancy (presence of options); and *iv.* Robustness (capacity to resist) [15,39,40].

Table 3 summarizes the description of each of these factors and their adaptation strategies, whereas Table 4 shows how they have been considered in different areas of water resource management.

Flexibility is the most studied factor because this factor is directly associated with the concept of resilience, which has been changing with the incorporation of additional factors. This factor evaluates the capacity to recover and is associated with the time of failure, reliability and recovery speed of a system from the perspective of risk management. Flexibility

Table 4.
Factors considered for the evaluation of resilience in different areas of water resource management.

Source	Flexibility	Resourcefulness	Redundancy	Robustness	Area of study
[14]		✓			Socio-Ecological
[17]	✓	✓		✓	Urban drainage
[18]	✓				Water resources
[19]		✓		✓	Socio-Ecological
[20]	✓	✓			Water supply
[21]				✓	Water resources
[22]		✓			Water resources
[23]	✓				Water resources
[24]	✓				Water resources
[25]	✓				Water resources
[26]	✓				Water resources
[27]	✓				Water resources
[28]	✓				Water resources
[29]	✓				Water resources
[30]	✓				Water supply
[31]	✓		✓	✓	Water supply
[32]	✓				Urban drainage
[33]	✓		✓		Urban drainage
[34]	✓	✓			Urban drainage
Factors/Total	15/19	6/19	2/19	4/19	
(%)	79	32	10	21	

Source: Created by author

has been quantified through semi-quantitative indices that measure the capacity to provide a service [20], mathematical functions that quantify the probability of system failure [23-27,29,32], system reliability [30,31] and indicators based on performance curves of a system that provide information on its behaviour before and after a disturbance [17,18,28,33,34].

Resourcefulness evaluates the availability of economic and social resources and is associated with the capacity to mobilize these resources in adverse conditions. This factor has been quantified through economic variables based on the estimation of damage caused to people and infrastructure [17,18,34], as well as social variables based on economic development, demographic trends, political stability, government policies, market incentives, media organization [14], resource diversity, community and institutional learning, system self-organization [19], governance [20], communication, risk perception, interaction between institutions and risk management policies and tools [22].

Redundancy evaluates the multiplicity of elements that allow the vital functions of a system to continue and is associated with the availability of redundant elements that carry out these functions. This factor has been quantified through metrics such as grouping and meshing coefficients [31], along with an index that combines the magnitude and duration of system failures where redundancy is evaluated by comparing how an existing system functions with and without redundant elements until failure occurs [33]. Of the four identified factors, this is the least considered because of its recent incorporation, which is primarily related to the evaluation of resilience in urban water systems [16,41].

Table 5.
Variables and indicators used to evaluate the resilience of UDS.

Factors	Variables	Indicators	Source
Flexibility	Capacity to recover	Index of failure	[23-27,29]
		Gradualness	[17,18]
		Duration of recovery	[17]
		Recovery rate	[18]
		Loss of recovery	[28]
		Environmental load capacity	[32]
		Recovery indicator	[33,34]
Resourcefulness	Response capacity	Response indicator	[34]
	Amplitude	Damage expected per year	[17,18]
		Expected number of affected individuals per year	[18]
Redundancy	Capacity of absorption	Severity	[33]
Robustness	Resistance capacity	Overload of the system	[17]
		Resistance threshold	[21]
	Response curve	Severity of the response	[21]
		Proportionality of the response	[21]
		Point of no recovery	[21]

Source: Created by author

Robustness evaluates the resistance of a system when faced with extreme or unexpected events and is associated with systems that function well, even under uncertain conditions. This factor has been quantified by analysing the resistance capacity of a system by estimating an overload [17] through a variable that addresses change and uncertainty [19]. This is based on a graph that describes the level at which one can establish how a system responds to different levels of disturbance [21] and through metrics such as the central dominance point, the density of articulation points, the density of joints, the spectral void and algebraic connectivity [31].

3.2. Variables and indicators of resilience for sustainable management of UDS

Based on the analysis of these factors, a group of variables and indicators was identified to evaluate the resilience of UDS; these are summarized in Table 5.

Flexibility is associated with the variable of recovery capacity, which evaluates the possibility of a drainage system to return to a normal or stable state after a disturbance; this variable includes several indicators and is the variable most studied by researchers.

The indicators proposed for this variable are the failure index, which quantifies the probability of system failure [23-27,29]; the gradualness, which measures the change in the response of a system with respect to the change of magnitude in a flood surge [17,18]; the recovery duration, which quantifies the time it takes for a system to recover from an unsatisfactory condition [17]; the recovery rate, which measures the recovery rate of the system after a flood [18]; the recovery loss, which quantifies the loss of quality in a system [28]; the environmental load capacity, which quantifies the amount of pollutant emissions that a system can endure [32]; and the recovery indicator, which measures the recovery time from a flood at each node of the system [33,34].

Resourcefulness is associated with two variables. One variable is the response capacity, which evaluates how the components of a drainage system respond to disturbances through a response indicator that allows for estimating the response magnitude in the area surrounding a flooded node [34]. The other variable is the amplitude [35], which evaluates the severity of damage expected in a drainage system after a disturbance through a yearly damage indicator that measures the average damage costs [17,18] and the expected number of affected individuals in a given year [18].

Redundancy is associated with the variable of absorption capacity [43], which evaluates the alternatives that can be offered by a drainage system after the failure of one or more of its component; the key indicator is severity, which measures the magnitude and duration of the maximum failure [33].

Robustness is associated with two variables. One variable is the resistance capacity, which evaluates the magnitude of the damage that a drainage system can endure through a system overload indicator that measures the greatest precipitation intensity that a system can endure [17]. The other variable is the response curve [21], which represents the aspects of robustness applicable to a UDS. The curve shows how a system responds to different disturbance levels through indicators such as the resistance threshold (which measures the point at which the response becomes greater than zero), the severity of the response (which corresponds to the point at which a system is no longer in a normal situation), the proportionality of the response (which relates the response change to the magnitude of the disturbance) and the point of no recovery (which is the point at which a system changes its identity into a new configuration).

Although this study identified resilience factors, variables and indicators in the sustainable management of UDS, continued research exploring other information sources (e.g., other databases besides *Scopus*, theses, government documents, etc.) is necessary to identify additional elements.

In addition, it will also be necessary to develop more comprehensive conceptual frameworks that can consider all of these factors, variables and indicators and validate them through case studies. However, combination of these factors and what could be the result of this combination is a pending work to be done. The elements identified in this study can serve as a first step in the development of these comprehensive frameworks.

4. Conclusions

The concept of resilience has evolved over the past 40 years, with a diversity of concepts arising from a narrow perspective with specific applications (engineering resilience) to a broader perspective that encompasses a more integral application context (socio-ecological resilience).

The concept of resilience has been scarcely studied as it pertains to UDS management, and the primary application has been in the study of flood risk. Therefore, much remains to be developed in this key field of research.

This study identified four key factors for the evaluation of resilience in water resources: flexibility, resourcefulness, redundancy and robustness. These factors evaluate the capacity to change, the mobilization of resources, the presence of options and the resistance capacity, respectively.

The following variables were identified to analyse resilience in UDS: recovery capacity, response capacity, amplitude, absorption capacity, resistance capacity and response curve. Associated indicators include the index of failure, gradualness, duration of recovery, rate of recovery, loss of recovery, environmental load capacity, recovery indicator, response indicator, expected damage per year, expected number of affected individuals per year, severity, system overload, resistance threshold, response severity, proportionality of response and point of no recovery.

Acknowledgments

The authors wish to express their gratitude for the financial support provided by the Universidad del Valle and Colciencias through Program 617 of 2013 for the financing of National Doctorate Studies granted to the first author and Program 745 of 2016 for the financing of Science, Technology and Innovation Projects and their contribution to the challenges faced by the country.

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