

# Case Studies to Integrate and Promote Global Issues in STEM Education



PHOTO: "The illusion of a new home". Nepal. Adrián Álvarez



# CASE STUDIES **Case Studies to Integrate and Promote Global Issues in STEM Education**

## EDITED BY

Engineering Sciences and Global Development Research Group,  
Universitat Politècnica de Catalunya

## COORDINATED BY

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## Preface

On September 25th 2015, member states of the United Nations approved the 2030 Agenda for Sustainable Development and a set of goals to guide its implementation. The Sustainable Development Goals (SDGs) are, therefore, action-oriented, concise and easy to communicate, limited in number (17), and universally applicable to all countries, taking into account the different realities and levels of development<sup>1</sup>. The 2030 Agenda is based on the need to harmonize three core elements: economic growth, social inclusion, and environmental protection. These elements are interconnected and are fundamental for the well-being of individuals, societies, and ecosystems.

In this context, it is expected that innovative solutions in the technical and technological field will play a key role in achieving most of the SDGs. Thus, future engineers and graduates in scientific-technical disciplines will be in a strong position to play a role of influence and transformation, both at local and international levels, assuming the responsibility of decisions that undoubtedly will have a significant impact on the social, environmental, and economic fields.

The university has the responsibility to actively participate promoting not only solidarity and equity in society but, ultimately, also sustainable development (SD), based on the activities that characterize universities: teaching, research, and transfer of knowledge and technology. In particular, universities will have to train and equip engineers with conceptual and practical tools that allow them to identify and face the challenges posed by an increasingly complex and interdependent society. In parallel, however, teaching staff face numerous obstacles when introducing the practicalities of development-related issues in the educational activity, such as poverty, inequalities, and global justice. This fact has a negative impact on the skills and abilities acquired by students during their training process.

Against this background, and with the aim of integrating SD as a cross-cutting element in all university courses in the science/technology field, the research group of Engineering Sciences and Global Development (EScGD) implemented the project “*Integrate and Promote Global Issues in Scientific-Technical Education*”. With the funding of Barcelona City Hall and the support of UPC’s Civil Engineering School Teaching Innovation Programme and UPC’s Cooperation for Development Centre, and under the umbrella of the project “*Global Dimension in Engineering Education (GDEE)*”<sup>2,3</sup>, this publication presents a set of teaching materials to enable professors to practically implement these transversal competences linked to the SDGs in the classroom. More specifically, the transversal competence of “*Sustainability and Social Commitment (SSC)*”, which comprises part of the current curriculum of the Universitat Politècnica de Catalunya (UPC; Barcelona, Spain).

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<sup>1</sup> United Nations General Assembly. 2015. *Transforming our world: the 2030 Agenda for Sustainable Development. Resolution A/RES/70/1*.

<sup>2</sup> GDEE. 2013. *Global Dimension in Engineering Education: Case Studies*. Recovered May 4, 2018, from <http://gdee.eu>.

<sup>3</sup> UPCommons. 2015. *Global Dimension in Engineering Education: Case studies for developing globally responsible engineers*. Recovered May 4, 2018, from <http://upcommons.upc.edu/handle/2117/88905>.

These materials are based on real-life experiences and are presented in the form of case studies<sup>4</sup>. In brief, each case study is made up of the following elements:

- A description of the case study, which includes an introduction (disciplines covered and expected learning outcomes), the context from a human development perspective, two teaching activities, and all pertinent annexes;
- A class presentation proposal, to assist academics in presenting the context in the classroom, and a description of teaching activities;
- A classroom activity, designed for a session of two to three hours, including work methodology and a possible solution. This activity aims to generate a debate around the context introduced as well as to provide the basic knowledge needed to autonomously carry out the homework activity;
- A homework activity, with a time requirement ranging from twelve hours to the entire semester course. Methodology and a possible solution are provided as well. The idea of this activity is to apply the technical and contextual knowledge acquired in the class;
- An evaluation rubric, as a useful tool to jointly evaluate the proposed activities.

Of note, the rubric associated with each case study has been adapted based on a general template designed to evaluate the transversal competence of SSC (see *Annex I*). The objectives related to these competences can be gradually distributed in three acquisition levels, consistent with the level of complexity of each course of the degree:

- Level 1: Able to systematically and critically analyze the global situation, to address sustainability both in an interdisciplinary manner and in the context of human development, and to recognize the social and environmental implications of professional activities in the same field;
- Level 2: Able to apply sustainability criteria and deontological codes of the profession to the design and evaluation of technological solutions;
- Level 3: Able to consider the social, economic, and environmental dimensions when applying solutions, and to carry out projects in a manner that is coherent with human development and sustainability.

The rubric specifies the different dimensions to be evaluated for each of the three levels of competences. For each dimension, and for each level, the attributes to be considered are detailed. Finally, a score is proposed based on the attributes addressed. In other words, the

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<sup>4</sup> EScGD (eds.). 2018. "Case Studies to Integrate and Promote Global Issues in STEM Education". Universitat Politècnica de Catalunya (UPC), Barcelona. Recovered May 4, 2018, from <http://www.eduglobalstem.cat/recursos/>

rubric shows the knowledge that students are expected to acquire and the criteria that will be used to evaluate the resolution content associated with the proposed activities.

In the proposed case studies, only the first two levels of acquisition are covered. The third level is related to a more extensive work or research, such as the final project at the end of university studies. In total, six case studies have been prepared, as detailed below:

**CS.1: Tanzanian's Rural Water Supply and Sanitation Programme: Introduction to Economy and Calculus for Engineering** (A. Pérez-Foguet and A. Garola)

**CS.2: Algebra and Large-Scale Dam Assessment: The Case of Merowe Dam in Sudan** (D. Requejo-Castro, J. Taberna-Torres and M. I. García-Planas)

**CS.3: Exploring the Use of Recycled Aggregates in Concrete Mix Proportion: An Alternative for Haiti?** (D. Requejo-Castro and M. Etxeberria)

**CS.4: Widening Horizons to the Design of a Pre-Stressed Concrete Slab: A Case Study in Barcelona** (D. Requejo-Castro and E. Oller)

**CS.5: Dimensioning a Drinking Water Distribution Network in Collique (Lima): Introduction to the Human Right to Water and Sanitation** (H. Grau-Huguet and E. Okpala)

**CS.6: Multivariate Analysis and Indices Construction: Data Mining Applied to the Rural Water and Sanitation Sector in Honduras** (C. Vergara Fuentes and A. Pérez-Foguet)

# Tanzanian's Rural Water Supply and Sanitation Programme: Introduction to Economy and Calculus for Engineering

Agustí Pérez Foguet and Alvar Garola



PHOTO: Rufiji river. Tanzania. Alejandro Jiménez Fdez. de Palencia



# CASE STUDIES **Tanzanian's Rural Water Supply and Sanitation Programme: Introduction to Economy and Calculus for Engineering**

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# 1

## TANZANIAN'S RURAL WATER SUPPLY AND SANITATION PROGRAMME: INTRODUCTION TO ECONOMY AND CALCULUS FOR ENGINEERING

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## 1. INTRODUCTION

In 2015, the UN General Assembly adopted the 2030 Agenda for Sustainable Development, a plan of action in favour of people, the planet, and prosperity, which also aims to strengthen universal peace and access to justice. The associated Sustainable Development Goals<sup>1</sup> (SDGs) seek to address the unfinished business and shortcomings of the Millennium Development Goals, which were used to monitor development progress from 2000 to 2015. Specific objectives for water and sanitation are also included within the SDG framework. Therefore, countries are and will be continuously asked to set their own national goals guided by world level ambitions and consensus, but taking into account national circumstances.

The Tanzanian government, as many others in the sub-Saharan region, has historically undertaken different plans to improve and increase access to water and sanitation services. In 2006, the National Rural Water Supply and Sanitation Programme (NRWSSP) was launched as part of a bigger plan to improve and increase access to water. To implement this ambitious programme and meet the corresponding objectives, it was necessary to develop a comprehensive resource allocation strategy that clarifies which factors should be considered, and how they should be weighted and applied.

With limited resources, adequate mechanisms are required to ensure that efforts and available resources are allocated to those water and sanitation activities that will produce the greatest positive impact for beneficiaries. Thus, evaluating the economic costs of interventions and the resulting benefits is critically important for effective resource allocation. A sound economic cost-benefit analysis is a useful tool for decision-makers (Boardman, 2006; European Commission, 2015).

Furthermore, when considering geographical equity or other crucial criteria from a political perspective, detailed analysis of disaggregated investments is usually included in the analyses. Surprisingly, in real applications, some specific issues related to water technologies, such as declining functionality rates with time, are not properly considered, leading to the expectable real output of planned investments being overstated (Jiménez and Pérez-Foguet, 2011a, 2012).

Data describing real situation of services and infrastructures of rural water sector were collected through the so-called Water Point Mapping (WPM) campaigns held in the country. The WPM approach is a well-documented and tool that is widely used by several non-governmental organizations in Africa for monitoring and for advocating activities about

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<sup>1</sup> Detailed information regarding the SDGs can be found at <http://www.un.org/sustainabledevelopment>.

access to water (Welle 2005). Jiménez and Pérez-Foguet (2008, 2010a, 2011b) worked on Tanzania's data intensively, and were able to recommend several proposals to improve sectorial water governance. The main interest in the case study presented here is to check the influence of some of their findings on the NRWSSP impact. In so doing, only a subset of data analyzed for Tanzania are used.

In this case study, students will first analyze how the NRWSSP allocated available resources and how the decisions were made by the Ministry of Water in collaboration with the World Bank, the principal donor of the programme. Second, an alternative is presented for analysis, based on the results found with regard to the declining functionality rate of water infrastructures over time. A comparison between these two different alternatives will allow the students to draw their conclusions on effective resource allocation for water and sanitation. Finally, a detailed analysis of the relationships between costs and performance of different technological solutions is introduced.

### 1.1. DISCIPLINES COVERED

This proposal has been prepared for a first-year degree of engineering. It fits within a basic economics of infrastructure course, and it can be used in conjunction with a basic course on multivariate calculus. The topics covered, and rationality of the case study, allows the proposal to be split into two parts: the first, to be used in the course of economics, and the second, in a course of calculus. In both cases, several activities are proposed in order to apply acquired concepts.

Specifically, this case study covers the allocation of national investments in rural water infrastructures in a developing country under different scenarios of available data.

An aim of the proposal is for that students to understand the different methodologies presented, and to be able to 1) analyze them through an economical cost-benefit analysis (ECBA); and 2) evaluate the marginal rate of substitution (MRS) between technological solutions.

Some basic concepts of multivariate calculus are covered, including time evolution of discrete systems, approximation of derivatives by increments, and the linearity of multivariate functions. The MRS is contextualized as an application of the implicit theorem, a basic pillar of multivariate calculus.

Real data have been simplified for conducting some illustrative calculus using standard spreadsheets.

## 1.2. LEARNING OUTCOMES

As a result of this case study, students are expected to be able to:

- Understand how governments develop a national water, sanitation and hygiene (WaSH) programme and allocate resources;
- Develop an economic cost-benefit analysis relevant to the WaSH sector;
- Understand how declining functionality rate of water infrastructure over time affects the expected impacts of a national WaSH programme;
- Compute time evolution of a discrete system;
- Relate variables through the implicit theorem;
- Approximate derivatives using incremental ratios

## 1.3. ACTIVITIES

Students should firstly receive a theoretical session in relation to the context and fundamentals presented in the next two sections of this document. First, brief descriptions should be introduced for: i) the national resources allocation in developing countries framework, ii) the context of The United Republic of Tanzania and its situation concerning the Water, Sanitation and Hygiene (WaSH) sector, and iii) the National Rural Water Supply and Sanitation Programme (NRWSSP). Second, an introduction should be provided for any (or all) of the three theoretical key topics of this case study: i) Economical Cost-Benefit Analysis (ECBA), ii) Implicit Function Theorem (IFT), and iii) Marginal Rate of Substitution (MRS).

Two activities are proposed and presented in this document, including the description of the supporting materials (standard spreadsheets). In the first activity, to be done within classroom time, small groups apply the basis of CBA analysis to this specific context. The results are discussed and complemented by the lecturer in the classroom. Session can finish by introducing the following homework activity, related to how the NRWSSP select beneficiaries of the programme and allocate corresponding resources geographically, once a reflection has been done on the CBA results.

In the second activity (homework activity), functionality rates of technical solutions effectively implemented in Tanzania are first described and then analyzed for their influence within the

simulation of NRWSSP outputs. Collected data describing real situation for different technological solutions are used to define alternative resources allocation with respect to the official one, and to define criteria for selecting technology prices, in two consecutive exercises.

The first proposed exercise is based on a spreadsheet implementation of the two allocation processes. It can be introduced in the classroom or assigned as homework in groups. A final discussion can be useful for closing the first exercise, provided that a qualitative analysis is asked for. The second exercise is also based on, practically, the use of a spreadsheet to compute different results. Basic multivariate calculus concepts such as linearity, partial derivatives approximation, and IFT are explicitly used, within the framework of an economic analysis based on MRS.

## 2. DESCRIPTION OF THE CONTEXT

### 2.1. WATER, SANITATION, AND HYGIENE

Water, sanitation and hygiene (WaSH) are essential for health, welfare, and livelihoods. Research shows that increased access and better services lead to higher levels of school achievement and improved economic productivity. The linkages between improvements in WaSH and the achievement of poverty, health, nutrition, education, and gender equality are proposed targets, and indicators for drinking-water, sanitation and hygiene, and sustainable economic growth are well established (WSSCC, 2014). Nonetheless, many people do not have basic water and sanitation services available. Considering the global WaSH situation, sub-Saharan African countries still have the lowest proportions of population with access to improved drinking water supply and sanitation facilities. Tanzania is one of the countries in the poorest situation.

The Sustainable Development Goals (SDGs) framework has established a new standard set of drinking water sources and sanitation categories that have been used for monitoring since 2015<sup>2</sup>. Service provision is expressed in terms of ladders, a sequence of levels of service with progressive added value. While ladders were used within the Millennium Development Goals<sup>3</sup> (MDGs) framework, they were simpler than they are now. At the time of this case study, the standard classification of WHO/JMP distinguished between improved and unimproved facilities. An improved drinking water source is one that, by the nature of its construction, adequately protects the source from outside contamination, particularly from

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<sup>2</sup> <http://www.wssinfo.org/definitions-methods/watsan-categories/>

<sup>3</sup> More information available at: <http://www.un.org/es/millenniumgoals/bkgd.shtml>

faecal matter. Improved sources include, but are not limited to, protected dug wells, boreholes, rainwater collection, and standpipes. Unimproved sources have been disaggregated into two categories: surface water and other unimproved sources. Surface water includes water collected directly from rivers, lakes, ponds, irrigation channels, and other surface sources. The latter includes unprotected dug wells, unprotected springs, and water delivered by cart or tanker. For sanitation, the same source is used to define the categories. An improved sanitation facility is one that hygienically separates human excreta from human contact. Unimproved sanitation facilities are those that do not ensure a hygienic separation of human excreta from human contact. In addition, shared or public sanitation facilities are considered unimproved as well. An example of an unimproved sanitation is open defecation, which is defined as defecation in fields, forests, bushes, bodies of water, or other open spaces.

## 2.2. NATIONAL RESOURCES ALLOCATION FRAMEWORK

A resource allocation framework sets out which factors should be considered, and how they should be weighted and applied. Considering the case study analyzed in this report, the framework for national resources allocation will be applied to the rural water supply and sanitation sector.

As it is very important to conduct good resource allocation within any development sector, adequate mechanisms are required to ensure that resources are allocated to those water and sanitation activities that are likely to have the greatest impact on achieving sector objectives. In addition, it is important to note that there are many factors to consider when assessing how to best allocate resources, between and within water and sanitation sub-sectors, yet it is equally important to remember that there is never one 'right' answer. Thus, determination of the best way to allocate resources within a country is a key decision, whether it is targeted at centrally managed projects or (increasingly) at local, decentralized projects. Considering that division of rural resources is a particularly difficult issue to resolve, this case study will contribute to understanding these concepts.

There is no single method that should be used to make decisions on resources allocation. Rather, several methods can be used, such as the subsector-driven approach, or the sector-objective-driven approach. The overall focus for the first of these is to allocate resources based on the importance of each subsector concerned. Using the second method, resource allocation is based on the objectives and targets of the sector as a whole, investing where the gaps are greatest. The case study presented in this report uses the first methodology to complete a "Sector Investment Plan" (SIP). Using this method, several institutions take part in what is called Sector Wide Approach, with key stakeholders meeting regularly to develop integrated sector policies, plans, and budgets. Further, donor support is allocated across

different institutions around the country, as funds are decentralized to local governments. Considering that geographical allocation is politically sensitive, the simplest method of allocation uses population levels, but this does not account for differing poverty levels, costs of providing services, and rates for accessing them. Calculating and comparing these factors for different regions requires elaborate formulas, and transparency is vital so that resource allocation decisions can be challenged and defended. However, cost-benefit analysis is rarely, if ever, the sole procedure used for making public investment and policy-related decisions. Views differ on how desirable this current situation is, but political reality dictates that many other interests are embedded in decisions made.

### 2.3. TANZANIA AT A GLANCE

The United Republic of Tanzania is located in Eastern Africa. Kenya and Uganda are to its north, Rwanda, Burundi, and the Democratic Republic of Congo to its west, and Zambia, Malawi, and Mozambique to its south. The country's eastern border lies on the Indian Ocean, with a coastline of 1,424 km. Tanzania has a total area of 945,087 km<sup>2</sup>.

Tanganyika became independent on 9<sup>th</sup> December 1961, and Zanzibar received its independence from the United Kingdom on 10<sup>th</sup> December 1963. On 26<sup>th</sup> April 1964, Tanganyika was united with Zanzibar to form the United Republic of Tanganyika and Zanzibar. The country was renamed the United Republic of Tanzania on October 29 of the same year. The name Tanzania is a blend of Tanganyika and Zanzibar and previously had no significance.

In 2005, the population of Tanzania was 36.2 million, with an annual growth rate of 2.9%. The population was estimated to be 46.2 million by the end of 2011 (in 2014). Its economy depends heavily on agriculture. Apart from that, tourism, mining, and small-scale industries are increasingly contributing to the national economic growth during the last years.

The government structure, including local administration, existed in Tanzania before independence. The government's decentralization policy was outlined in the 1998 Policy Paper on Local Government Reform and was characterized by the transfer of competencies from central to distinct legal entities, which have wide autonomy. The policy was expected to reduce poverty by improving service delivery, thanks to effective and autonomous Local Government Authorities (LGAs)<sup>4</sup>.

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<sup>4</sup> Further details on historical evolution of the sector can be found in Jiménez and Pérez-Foguet (2010b)

## 2.4. THE NATIONAL RURAL WATER SUPPLY AND SANITATION PROGRAMME

The Tanzanian government, like many others in the sub-Saharan region, pushed an ambitious plan to improve and increase access to water: the Water Sector Development Programme. This plan includes three sub-programmes: for water resources management and development, for rural water supply and sanitation (the NRWSSP), and for urban water supply and sewerage. The central government plays the role of coordinator and facilitator in the water subsector, while the district level holds the main implementation responsibilities. At the time of the Programme design, Tanzania had an estimated rural population of 25.9 million, and the reported rural water coverage was 53%. Giné and Pérez-Foguet (2008) and Jiménez and Pérez-Foguet (2011c) present general overviews of the NRWSSP. Key facts and figures are summarized in the following:

### Targets

The NRWSSP establishes targets for the percentage of rural population with sustainable and equitable access to safe water:

- At least 65% by 2010 (a goal set by the National Strategy for Growth and Reduction of Poverty, also known as MKUKUTA);
- At least 74% by mid-2015, as specified by the MDGs;
- At least 90% by 2025.

### Population Growth Estimation

Investment requirements are based on the rural district census population and growth rate figures, as reported in the 2002 census. The rural census includes small towns with populations under 50,000 inhabitants. For the purposes of estimating investment requirements in this report, the total rural and small towns population is estimated at 30 million as of 2004, projected to grow to 41 million by 2025. Overall, the fulfilment of the above targets will require extending water supply coverage to an additional 33.8 million people from 2005 to 2025.

### Cost Estimation

The estimated costs for the rural component (i.e., excluding small towns) is US\$ 1.61 billion, with US\$ 1.46 billion for capital investment, including rehabilitation, US\$ 51 million for management and operational support to districts, nearly US\$ 17 million for institutional



strengthening and development, and US\$ 74 million for contingencies (Ministry of Water 2006).

### General Planning Process

The process at district levels combines approaches from two different directions: top-down and bottom-up. Every year, the LGA decides on their budget based on allocations to their districts, which is submitted to the Ministry of Funds (MoF). The MoF makes the final decision and approves the national budget. The same system is used at the ministry level, and the development grants are allocated only to qualified districts. However, the mechanism is different, as the Ministry allocates funds to qualified districts according to formulas, and the LGA makes the final selection of beneficiaries after discussing it during a full council meeting.

### Key Aspects at the Ministry level

For this case study, we will concentrate in the Ministry's mechanisms of decision-making. The allocation of NRWSSP resources is affected by the following responsibilities: design of the Program, allocation of resources, and formulation of guidelines to help LGAs.

In reference to the design of the Program, it is important to notice that calculation of water points for each district is based on two general principles: i) current coverage rates – the programme aims to increase coverage levels in those district showing lowest coverage, and ii) technological options presented in each district. Hence, costs are assigned based on the foreseen technology mix. This technology mix was the main driver for cost calculation.

With respect to the allocation of resources, allocation of NRWSSP funds from ministry to district level is driven by formulas. Three different water budgets are in place:

- *The Development Budget* (also named the Capital Development Grant) is used for implementing water infrastructure and constructing demonstration latrines. This represents 91.22% of the estimated total budget of the Program. The proportion of unserved population living in one district as compared with the total unserved population in the country overall is taken as the parameter for allocating funds. This represents a major shift between the intended goal and the implementation of the plan; that is, as the largest groups of unserved people will be targeted, there will not be territorial equity;
- *The Recurrent Budget* (also named the Rural Water Block Grant) is the investment assigned for the annual supervision, monitoring, and support of water services in

rural communities. In this budget, priority is given to unserved areas (with an assignment of 90%);

- *The Capacity Building Grant.* For this grant, the same amount is allocated regardless of the district.

### Planning Process at Ministry Level

The NRWSSP has a planning process that assigns the main responsibilities at different government levels, which affects the allocation of resources related to the Programme. At the Ministry of Water, the main responsibility is the design of the RWSSP, which includes the allocation of funds to districts and preparation of guidelines for implementation. This allocation of funds, which is the main topic of this case study, is analyzed in the following paragraphs.

The forecasted allocation of resources is derived from three general principles:

- Districts with less coverage will receive more funds to bring their level of service closer to the national level. In 2004, the reported coverage by district ranged from 6.4 to 91.8%. The NRWSSP aims for all districts to be in the range of 80% to 95% by 2025.
- The proposed water supply technologies and related costs are derived from the existing mix of technologies in each district, combined with expert opinions and a demand assessment study performed in 18 districts.
- Government investment forecasts for 2005–2025 assume that only 25% of all rural systems in existence in 2004 will require major investments for rehabilitation during that period (Ministry of Water 2006, “5.6.1.3. Rehabilitation of Existing Systems”). Additionally, capital investment for major system rehabilitation is assumed to account for 66% of the cost of new water supply services by technology. As a result of these two assumptions, only US\$ 77 million of government funds has been set aside for rehabilitation of pre-existing infrastructure (Ministry of Water 2006, “Appendix 5”).

## 3. THEORETICAL BACKGROUND

The three basic concepts to work on during this case study are briefly presented in this section: i) the Economic Cost – Benefit Analysis (CBA), ii) the Implicit Function Theorem (IFT), and iii) the Marginal Rate of Substitution (MRS).

### 3.1. ECONOMIC COST – BENEFIT ANALYSIS (CBA)

Economic principles that can inform water policy debates rest on the concepts of benefit and cost. The general cost–benefit framework (Boardman, 2006; European Commission, 2015) can provide a comparison of total economic gains and losses resulting from a proposed water policy (Brouwer and Pearce, 2005). The approach is used as an analytical technique for measuring the economic efficiency of public actions by translating positive and negative effects to a common measure (normally, money). For public water policy proposals, maximum beneficial use of water requires that government formulate, implement, and evaluate their water resource programmes using these economic principles. Using methods that are grounded in time-tested economic principles, the cost–benefit analysis can provide decision-makers with a comparison of the impacts of two or more water policy options.

Using this methodology, it is possible to examine the growth of the social benefit derived from the water used rather than just the quantity of water used. Economic efficiency, measured as the difference between added benefits and added costs, could inform water managers and the public about the economic impacts of water programmes for addressing peace, development, health, the environment, climate, and poverty (Ward, 2012). Improving water supply and sanitation and water resource management boosts countries' economic growth and contributes greatly to poverty eradication (SIWI, 2005).

The cost-benefit analysis, in practice, includes the monetarization of health-related costs and benefits, among others (Malloy-Good and Smith, 2008). There are different options for doing this. For instance, the DALY (Disability-Adjusted Life Year) approach was developed in the early 1990s to provide a broader measure of health than simply “deaths avoided”. DALYs go beyond classifying individuals as either living or dead and instead incorporate standards of health on the basis of disability weights provided by the WHO. As a result, “DALY measures not only the additional years of life gained by an intervention but also the improved health that people enjoy as a consequence” (Jamison, 2006).

### 3.2. IMPLICIT FUNCTION THEOREM (IFT)

In multivariable calculus, the implicit function theorem allows derivatives of some variables to be related with respect to others in a neighbourhood of a specific point, given an implicit vector function that relates both sets of variables. The theorem states that if the  $m$  equations represented by  $F(x_1, \dots, x_n, y_1, \dots, y_m) = F(x, y) = 0$  satisfies some mild conditions on its partial derivatives (i.e. with  $F$  as continuously differentiable functions and invertible Jacobian matrix of  $F$  with respect to  $y$ ,  $J_{F,y}(x, y)$ ), then one can express the  $m$  variables  $y_i$  in terms of the  $n$  variables  $x_j$  as  $y_i = f_i(x)$ , though not necessarily with an analytic expression. Moreover, if

the above-mentioned conditions are satisfied, and considering  $y = f(x)$ , the following relationship holds:

$$\frac{\partial f}{\partial x_j}(x) = -J_{F,y}(x, f(x))^{-1} \frac{\partial F}{\partial x_j}(x, f(x))$$

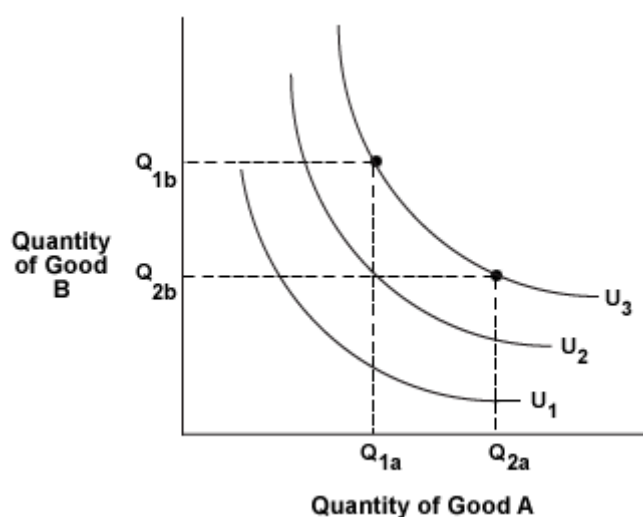
In particular, when addressing a problem with only two variables  $x$  and  $y$  ( $m = n = 1$ ) subject to  $F(x,y)$  equal to a constant value, the previous equation can be simplified and expressed in terms of the differentials of  $x$  and  $y$ :

$$\frac{\partial y}{\partial x}(x) = -\frac{\frac{\partial F}{\partial x}}{\frac{\partial F}{\partial y}} = -\left(\frac{dy}{dx}\right)_{F=0}$$

This expression is the base of the concept of the MRS (see following section).

### 3.3. MARGINAL RATE OF SUBSTITUTION (MRS)

A practical use of the implicit function can be found in the field of economics. Specifically, this use refers to MRS, which is the rate at which a consumer is ready to give up one good in exchange for another good while maintaining the same level of utility. Illustratively, the two different goods might be the variables “unit cost” and “functionality”, and the utility might be associated to the total cost of the Programme.



**Figure 1** Curves of equal utility for different quantities of goods A and B.

Mathematically, the MRS corresponds to the slope of an indifference curve passing through the consumption combination in question (implicit derivate). As shown in *Figure 1*, an indifference curve connects points on a graph representing different quantities of two goods, points between which a consumer is indifferent. That is, the consumer has no preference for one combination of goods over a different combination along the same curve.

Thus, MRS of x for y is the amount of y for which a consumer is willing to exchange x locally, maintaining the same level of utility (U).

$$MRS_{xy} = - \left( \frac{dy}{dx} \right)_{U=U_0} = \frac{\frac{\partial U}{\partial x}}{\frac{\partial U}{\partial y}}$$

As an example: if the  $MRS_{xy} = 2$ , two units of y must be sacrificed to obtain one additional unit of x. Note that, in general, the MRS is different at each point of the indifference curve.

#### 4. CLASS ACTIVITY

As outlined above, NRWSSP is implemented through the construction or the rehabilitation of water systems. Costs of water access improvement vary principally with the infrastructure, depending on the technology adopted and the population covered. Benefits are not explicitly quantified. The targets are fixed, and the benefits are implicitly assumed to be greater than the costs. In this first activity, the CBA is used to check this usual hypothesis.

In groups of three or four students, list costs and benefits that should be taken into account in order to make an economic cost-benefit analysis. *Table 1* has been provided to help students create the list (Malloy-Good and Smith, 2008). As many benefits and costs as possible should be included. In addition, these aspects should be discussed. It is important to note that the table does not include other types of costs and benefits (environmental, overproduction, etc.), which however should be included for a complete analysis. After the identification of costs and benefits, students can look for ways to quantify them, collect all different valorisations, and evaluate alternatives for a specific intervention. The groups should work on a demonstrative proposal of using CBA under professor supervision.

**Table 1** Template for task resolution.

BENEFICIARY	DIRECT ECONOMIC BENEFITS OF AVOIDING DIARRHEAL DISEASE	INDIRECT ECONOMIC BENEFITS RELATED TO HEALTH IMPROVEMENT	NON-HEALTH BENEFITS RELATED TO WATER AND SANITATION IMPROVEMENT

#### 4.1. SOLUTION AND EVALUATION CRITERIA

An exemplary filled-out *Table 1* (which should be created during the class activity) is presented below, in which the economic benefits arising from water and sanitation improvements are presented. Tables filled by the students should be discussed in class to allow different levels of benefits to be included and to be compared with the costs (investment and maintenance) of carrying out the program.

BENEFICIARY	DIRECT ECONOMIC BENEFITS OF AVOIDING DIARRHEAL DISEASE	INDIRECT ECONOMIC BENEFITS RELATED TO HEALTH IMPROVEMENT	NON-HEALTH BENEFITS RELATED TO WATER AND SANITATION IMPROVEMENT
Health sector	- Less expenditure on treating diarrheal disease	- Value of less health workers falling sick with diarrhoea	- More carefully managed environment and effect on vectors
Patients	- Less expenditure on treating diarrheal disease and related cost - Less expenditure on transport for seeking treatment - Less time loss due to seeking treatment	- Value of avoiding lost days at work or school - Value of avoiding lost time of caring for sick babies - Value of avoiding loss of death	- More carefully managed environment and effect on vectors

BENEFICIARY	DIRECT ECONOMIC BENEFITS OF AVOIDING DIARRHEAL DISEASE	INDIRECT ECONOMIC BENEFITS RELATED TO HEALTH IMPROVEMENT	NON-HEALTH BENEFITS RELATED TO WATER AND SANITATION IMPROVEMENT
Consumers			<ul style="list-style-type: none"> <li>- Time savings related to water collection or accessing sanitary facilities; ease of access to water supply frees up more time for child care, domestic hygiene, food preparation, relaxation, organizing oneself, education, and production</li> <li>- Labour-savings devices in household</li> <li>- Switch away from more expensive water sources</li> <li>- Rise in property value</li> <li>- Leisure activities and non-use value</li> <li>- Improved school attendance (if boys and girls are in charge of water collection duties)</li> </ul>
Agricultural and industrial sectors	- Less expenditure on treatment of employees with diarrhoea disease	- Less lowered productivity impact of workers being off sick	<ul style="list-style-type: none"> <li>- Benefits to agriculture and industry of improved water supply</li> <li>- Saving time and/or income</li> <li>- Generating technologies and changes in land use</li> </ul>

### CHILD MORTALITY

$$\boxed{\text{Birth rate } 0.036} \times \boxed{\text{Rural population}} \times \boxed{\text{Reduction death rate } 2.08} \times \boxed{\text{Average working years } 30} \times \boxed{\text{GNI x capita}}$$

Reduction child mortality	Assuming 30 years average working life		
Birth rate	36/1000 people		Reduction per year
Child mortality rate	2005	63.7	2.08
	2016	40.8	

	2005	2006	2007
Child mortality rate		2,591,267.24 US\$	2,858,520.42 US\$

**Figure 2** Monetization of reduction of child mortality.

### CBA (2005 - 2025)

Year		2005	2006	2007
Cost		15,338,000 US\$	22,085,000 US\$	24,353,000 US\$
Benefits	Diarrhoea	-	7,213,575 US\$	7,957,556
	Increment in land cultivated / agricultural productivity	-	1,083,200 US\$	1,083,200 US\$
	Time reduced	-	61,707,441 US\$	68,071,705 US\$
	Life expectancy	-	158,442,498 US\$	174,783,638 US\$
	Child mortality	-	2,591,267 US\$	2,858,520 US\$
Total		15,338,000 US\$	208,952,982 US\$	230,401,620 US\$
Applying discount rate of 12%		15,338,000 US\$	186,565,162 US\$	183,674,761 US\$
Total benefit		2,074,880,741 US\$	IRR	1,215%

**Figure 3** Example of Cost-Benefit Analysis (CBA).

Figure 2 shows an example of monetization of child mortality reduction in a CBA. The proposal was elaborated by a group of students<sup>5</sup> of first year of Civil Engineering studies in Barcelona (UPC), course 2017-2018, on the bases of Fink et al. (2011). The steps to compute the monetary value are:

- Assess the birth rate of the rural population in Tanzania;
- Estimate how child mortality would vary with better quality conditions and water supplies;
- Find a monetary value to estimate the benefit of reducing child mortality. In this case, the average apparent productivity (in terms of GDP / capita) adjusted for each year of working life is used.

Both data and values should be adapted to the information available. In general, this approach underestimates the real value of the reduction, since it only measures it from the

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<sup>5</sup> Natàlia Badia, Arnau Ferrer, Jonathan Sanz, and Oriol Corvo



contribution to the creation of wealth, but it allows this benefit to be monetized and to be added to the other benefits and costs.

*Figure 3* shows some of the standard indicators used in CBA. Cost and benefits of the first 3 years of the program are explicitly detailed. Both costs and benefits are summed, and the monetary fluxes are expressed in constant terms using a discount rate of 12%, which is the social value used in a country such as Tanzania.

The sum of these updated flows allows two basic indicators of a cost-benefit analysis to be obtained: the Net Present Value (NPV), and the Internal Rate of Return (IRR). A positive NPV means that the project offers more benefits than costs. Higher values of the NPV imply a higher net benefit created by the project. It should be highlighted that the benefits are not financial, but rather a quantification of the improvements in the quality of life of the population. On the other hand, the IRR shows the average annual return obtained. Higher IRR implies greater social profitability of the project.

### **Evaluation Criteria**

In order to provide an objective and transparent evaluation system for students, we propose to use a rubric (see *Annexes V and VI*). In brief, the rubric shows: i) the knowledge that students are expected to acquire; and ii) the criteria used to evaluate the content of the answers associated with the proposed activities.

Considering that this case study can be used within economy and calculus subjects, we provide two different rubrics. For this activity evaluation, common criteria are used, as it is suggested that it be carried out regardless of whether this material will be used for economy or calculus lectures. Only a small difference should be highlighted: if this case study is used for a calculus topic, an extra task to answer is detailed within the rubric, in which students are expected to work on the dimension of “social commitment” (see *Annex VI*).

The rubric should first be provided to the students, in order to inform them how they will be evaluated. Giving the students some guidance may be necessary to allow them to focus on the specific goals (in terms of answers).

To facilitate evaluation, each group must submit (or give in paper format) the answers to the professor at the end of the class. These answers will be evaluated based on the criteria from the rubric. However, the teacher is free to choose an alternative evaluation method that might be considered more appropriate.

## 5. HOMEWORK ACTIVITY

The homework activity has been designed for small groups (3 or 4 students) and to last between 6 and 8 hours.

For the information needed for the activity, data that are needed to solve the exercise are first presented. Two investment alternatives are then described: i) the standard procedure focused on construction of a new infrastructure (Option A), and ii) an alternative approach (Option B), which considers that there is a decrease of the infrastructure functionality rate with time, and that, therefore, the rehabilitation of new investments has to be considered within the project design.

After this introduction, the main questions of the homework activity are proposed.

### 5.1. DATA

#### The Technology Mix

On the basis of the populations to be provided with new access to services, the water supply coverage is disaggregated by technology type throughout the project period (2005–2025). The mix of technologies projected for 2025 closely resembles the estimated mix of technologies currently in use across the country. For this activity, these water point technologies are simplified to just two types:

- *“Hand pump & shallow well”*. The well is a deep hole that has been driven, bored, or drilled, with the purpose of reaching groundwater supplies. It is constructed with casing or pipes that prevents the small diameter hole from caving in and protect the water source from infiltration by run-off water. Water is delivered from a tube well or through a pump, which may be powered by human, animal, wind, electric, diesel, or solar means.
- *“Pumped & piped system”*. This is defined as a water service pipe connected with in-house plumbing to one or more taps (e.g. in the kitchen and bathroom).

#### Water Supply Needs

Future needs to be met by the Programme were determined by attempting to satisfy (or to exceed) three criteria at the Programme and district level. Based on 2002 census data, current coverage levels, and satisfaction of these objectives, the number of systems needed in every district was determined, which were distributed during the project time-life.

“Systems” tab in *Annex 1* shows the systems needed to be constructed every year for the complete coverage of every district. In *Table 2*, the total number of systems to be constructed for the entire period of the project is summarized. In this case study, only 10 districts are considered.

**Table 2** Coverage levels in number of systems to be constructed

	2005 - 2025	
REGION NAME	HANDPUMP & SHALLOW WELL (Num. Systems)	SINGLE PUMPED & PIPED SYSTEM (Num. Systems)
Dodoma	1,518	1,021
Iringa	2,111	106
Tabora	5,429	1,092
Mara	8,762	2,667
Kilimanjaro	2,942	0
Shinyanga	9,882	923
Mbeya	14,865	2,597
Morogoro	7,100	1,523
Kagera	14,719	967
Mwanza	3,294	1,230
<b>TOTAL</b>	<b>70,622</b>	<b>12,126</b>

### Unit Costs

The suppliers for the project have determined unitary costs for every technology and for both construction and rehabilitation. Figures are presented in “Unit costs” tab in *Annex 1*. Capital investment in major system rehabilitation is assumed to represent 60% of the cost of new water supply services.

### Funding

The available funds for the years’ duration of the project have been estimated. The funds are provided as shown in *Table 3* by the government of Tanzania, NGOs, and international donors.

**Table 3** *Funding sources*

SOURCE	2005 - 2025 (US\$)
Government of Tanzania	412,512,800
Donors	551,816,367
No Government Organization	112,100,000
<b>TOTAL</b>	<b>1,076,429,167</b>

**Table 4** *Total costs relative to Option A*

REGION NAME	2005 - 2025 (US\$)
Dodoma	71,795,500
Iringa	15,755,750
Tabora	92,961,250
Mara	207,926,500
Kilimanjaro	12,503,500
Shinyanga	101,070,500
Mbeya	229,384,250
Morogoro	127,647,000
Kagera	124,443,750
Mwanza	92,719,500
<b>TOTAL</b>	<b>1,076,207,500</b>

## 5.2. ALLOCATION ALTERNATIVES: OPTION A

Starting from the data presented, it is possible to define how much the cost will be depending on how the project is carried out. Having the cost estimates, it is interesting to analyze different options about how to invest and distribute the funds.

The first option, Option A, represents how NRWSSP planned and carried out the project by basically constructing the systems needed during the project period. In this option, the funds

considered are just those required to construct new systems. This does not include a rehabilitation of the new non-working systems.

### Cost Option A

It is possible to determine the cost for every year of the project, as well as the total cost of the implementation. For this, the systems needed for the unit costs of construction are multiplied. The “Cost (Option A)” page in *Annex 1* presents how the costs are distributed during the project. In *Table 4*, the total costs are summarized. It is clear that the funds are sufficient to cover all investments detailed in *Table 3* (e.g., US\$ 1,076,429,167).

## 5.3. ALLOCATION ALTERNATIVES: OPTION B

As stated by previous studies, a proportion of all systems (that is, those already in function at the beginning of the programme, and those that are newly installed) require substantial re-investment in order to continue to provide adequate service at some point over the Programme's timeframe. This option introduces the concept of rehabilitation of the “dead” systems during the project period, and opts for considering these rehabilitations as a part of the programme itself. Values of functionality rates by technology are estimated from monitoring data available.

### The WaterAid Water Point mapping

The water point mapping (WPM) approach was designed as a procedure for measuring access to water in rural areas. WPM can be defined as “an exercise whereby the geographical positions of all improved water points (WPs) in an area are gathered in addition to management, technical, and demographical information. This information is collected using GPS and a questionnaire carried out at each WP. Data are entered into a geographical information system and then are correlated with available demographic, administrative, and physical data. Information is then displayed using digital maps” (Welle, 2005). WPM has been used extensively by Water Aid and other NGOs in various African countries for a number of years, being first used in Tanzania in 2005. So far, 51 out of 132 districts of Tanzania have been mapped, and the Tanzanian government plans to extend it across the whole country. WPM calculates coverage through density, which is equal to the number of improved WPs per 1,000 inhabitants (Stoupy and Sudgen, 2003; Jiménez and Pérez-Foguet, 2008).

Between 2005 and 2006, WaterAid collected data from 5921 improved WPs in 15 districts. As a result, the percentage of functional WPs over the years was estimated for different technologies. *Table 5* presents the functionality rates for two of them. Hand pumps

functionality – function over time – dropped from 61% in the first five years to 13% in the 25-year period. Similarly, pumped and piped systems started at 66% but dropped to 22% in the 25-year period.

**Table 5** Percentage of functional water points by technology. Adapted from: Jimenez and Pérez-Foguet 2011a

Technology	Functional Water Points (%)					
	+25 years	25 – 20 years	20 – 15 years	15 – 10 years	10 – 5 years	5-0 years
Shallow well and hand pump	13	29	41	51	61	100
Electric or diesel, pumped or piped	22	45	48	62	66	100

### Rehabilitation of Non-functional Systems

Once the mortality of the systems is known, the number of systems for rehabilitation during the project can be determined. This option contemplates only the rehabilitation of the systems constructed during the project; after rehabilitation has taken place, the rehabilitated system performs as a new one in the future. *Table 6* shows that no systems are available to be rehabilitated during the first period. In the second period, the dead systems from the first period will need to be considered. Thus, the total new systems of the second period are the sum of the systems built in the first period that are rehabilitated, plus the newly constructed ones. The third period is the same except that the dead systems from the two previous periods are considered in different percentages and, consequently, for the fourth period. The “Rehabilitation” tab in *Annex 1* shows the complete data for all districts during the project.

**Table 6** Number of systems for rehabilitation.

2005 - 2010		2011 - 2015		2016 - 2020		2021 - 2025	
Hand pump & shallow well	Single pumped & Piped	Hand pump & shallow well	Single pumped & Piped	Hand pump & shallow well	Single pumped & Piped	Hand pump & shallow well	Single pumped & Piped
(systems)	(systems)	(systems)	(systems)	(systems)	(systems)	(systems)	(systems)
0	0	6,615	765	11,861	1,217	11,599	2,142

### Cost Option B

In this case, and in order to obtain the estimated cost, the newly constructed systems must be multiplied per construction unit cost. Further, multiplying the rehabilitated ones times rehabilitation unit cost of each technology is also required. As expected, the total cost is higher than the previous option. Therefore, the funds are not enough to cover all project costs.

To face this problem, a flat rate reduction of the investments is considered. The percentage of reduction is obtained by dividing the total cost of the option by the funds available. The result shows that it is possible to cover the districts in 82% of the service, such that the option should be considered of building only 82% of the initial prevision of systems, to have enough funds. These relations are shown in "Cost (Option B)" tab of *Annex 1* and here in *Table 7*.

**Table 7** Total cost in relation to Option B.

REGION NAME	2005 - 2025 (US\$)	2005 - 2025 (US\$) - 82% construction -
Dodoma	83,055,269	68,183,009
Iringa	20,787,336	17,065,059
Tabora	107,313,848	88,097,736
Mara	240,021,582	197,042,210
Kilimanjaro	14,317,593	11,753,819
Shinyanga	132,056,873	108,410,160
Mbeya	296,865,306	243,707,234
Morogoro	164,773,727	135,268,583
Kagera	143,706,670	117,973,890
Mwanza	108,324,563	88,927,466
<b>TOTAL</b>	<b>1,311,222,766</b>	<b>1,076,429,167</b>

## 5.4. EXERCISE 1

For this exercise, students will work in small groups, which can be the same or different groups as for the class activity. The proposal requires carrying out an analysis of the results presented previously, taking advantage of the automation of calculus thanks to the systematic use of a spreadsheet. The following questions are proposed to get closer to the real problem of choosing between implementation strategies and budget distribution criteria, considering the influence of different technologies:

- In *Annex 1*, “Analysis” tab, a comparison of both project implementation approaches is provided. Specifically, the variation of the number of systems in service along time is presented. Describe briefly the resulting graphs and the implications of executing each option. List in detail and discuss the pros and cons of each option. Which one would you implement?
- Consider the new percentages of functionality and unit costs. To do this, change the data in “Unit costs” and “% functional” tabs provided in *Annex 1* as specified below. Could be these important enough to change the decision of one option?

**a) Scenario 1:** Unit cost and functionality rate decrease (“cheaper but less robust”)

**Table 8** Data setting for Scenario 1

Technology	Unit cost / system (US\$)	
	Construction	Rehabilitation
Shallow well and hand pump	3,500	2,100
Electric or diesel, pumped or piped	52,706	31,624

Technology	Functional Water Points (%)					
	+25 years	25 – 20 years	20 – 15 years	15 – 10 years	10 – 5 years	5-0 years
Shallow well and hand pump	9	19	27	33	40	100
Electric or diesel, pumped or piped	14	23	33	41	43	100



**b) Scenario 2:** Unit cost and functionality rate increase (“more expensive but more durable”).

**Table 9** Data setting for Scenario 2

Technology	Unit cost / system (US\$)	
	Construction	Rehabilitation
Shallow well and hand pump	5,000	3,000
Electric or diesel, pumped or piped	75,294	45,176

Technology	% of Functional Water Points					
	+25 years	25 – 20 years	20 – 15 years	15 – 10 years	10 – 5 years	5-0 years
Shallow well and hand pump	17	38	54	67	80	100
Electric or diesel, pumped or piped	29	46	66	81	87	100

- Finally, new data are provided to be included for prioritizing “Option B”: The total population by 2025 and the mean annual rainfall by region (see *Table 10*). Considering that the total funds are fixed, and all information available, reflect on the possible strategies and propose alternatives to the flat-rate reduction to 82%. If the funds for the project were not fixed, could you propose ways to increase them?

**Table 10** Estimated population in Tanzania by 2025 and mean annual rainfall from 1982-2012, by region

REGION NAME	TOTAL POPULATION 2025 (1000s of people)	MEAN ANNUAL RAINFALL (1982 - 2012) (mm)
Dodoma	3,306	500 - 750
Iringa	209	750 - 1,000
Tabora	2,720	750 - 1,000
Mara	4,226	750 - 1,000
Kilimanjaro	1,673	500 - 750

REGION NAME	TOTAL POPULATION 2025 (1000s of people)	MEAN ANNUAL RAINFALL (1982 - 2012) (mm)
Shinyanga	4,891	1,000 - 1,250
Mbeya	7,292	750 - 1,000
Morogoro	4,967	750 - 1,000
Kagera	7,108	1,500 - 1,750
Mwanza	4,642	1,000 - 1,250

## 5.5. EXERCISE 2

In this second exercise, the reference used is Option B as defined previously but with enough funding to cover all districts at 100%. Additionally, for simplification, only two parameters are initially included in the analysis: i) the unit costs of a shallow well & hand pump ( $C_c$ ), and ii) its functionality in the period of the first 5 years ( $F_5$ ). These variables are identified in *Annex 2* with filled colour. When modifying their values, all spreadsheet results are updated.

The starting point of the exercise is set up with the initial values detailed in *Annex 2*. The new constructors of water points are considered to offer different unit costs for a shallow well & hand pump, together with new water system's functionality rates. The main objective of this exercise is to assess to what extent it is worth accepting those changes. To do this, the following steps are proposed:

- The existing values of  $C_c$  and  $F_5$  in *Annex 2* ("Unit costs" and "% functional" tabs) should be modified according to the values provided in the following *Table*. Then, resulted estimated total cost (T) should be filled in where corresponding.

	$F_5 = 41$	$F_5 = 51$	$F_5 = 61$	$F_5 = 71$	$F_5 = 81$
$C_c = 4,050$					
$C_c = 4,150$					
$C_c = 4,250$			1,311,222,766		
$C_c = 4,350$					
$C_c = 4,450$					

- Does the total cost (T) vary linearly with those two variables? Is the total cost linear in  $C_c$ ? And in  $F_5$ ? Justify and explain the results obtained.
- The MRS between both parameters ( $C_c$ ,  $F_5$ ) at (4.250, 61) should be approximated using first order incremental differences. Which is its unit of measurement of  $MRS_{F_5, C_c}$ ? Explain briefly its meaning. Which values for incremental approximations to derivatives do you propose? Justify them.

$$MRS_{F_5, C_c} = - \left( \frac{dC_c}{dF_5} \right) = - \left( \frac{\frac{dT}{dF_5}}{\frac{dT}{dC_c}} \right) \quad \text{with} \quad \frac{dT}{dF_5} \approx \frac{\Delta T}{\Delta F_5} \quad \text{and} \quad \frac{dT}{dC_c} \approx \frac{\Delta T}{\Delta C_c}$$

- A new scenario is set up. New suppliers ensure a functionality of 85% ( $F_5 = 85$ ) for the first 5 years, for both shallow wells & hand pumps. How much would you be willing to pay for those new systems? Use MRS concept to compute the limit value. Once computed, check if the same total cost (T), regarding the initial situation, is obtained by substituting the new values of the variables.

$$T(C_{4.250}, F_{561}) = T(C_{CX}, F_{585})$$

- In general, the unit costs vary with technology, as presented in Exercise 1. Thus, there will be more than two variables of interest from a MRS point of view, e.g. two unit costs and two functionality rates for the first five years (one pair of parameters by technology, at least). Explain how to use the Implicit Function Theorem to compute the derivatives of any of these variables with respect to the others while considering some costs fixed. Which are the key points to take into account to solve the problem in these general cases?

## 5.6. SOLUTION AND EVALUATION CRITERIA

### Solution for Exercise 1

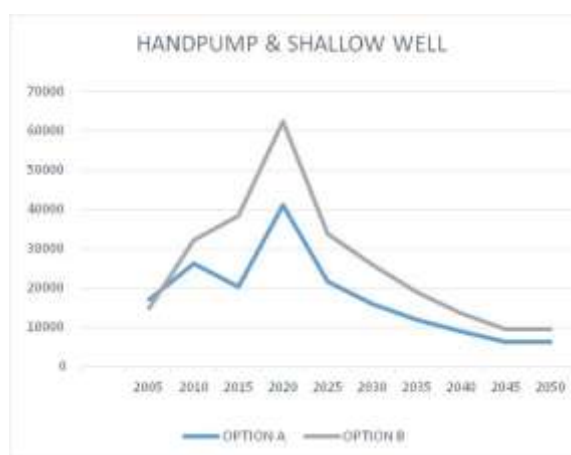
Figures provided in *Annex 1* ("Analysis" tab) show the impact of considering system rehabilitation during the execution of the Programme. During the first period of project implementation (e.g., the first 5 years), Option A provides more service than Option B. Nevertheless, as the time passes, Option B ensures a higher amount of systems in service. Thus, it can be concluded that the best option is to consider and ensure the rehabilitation of the systems, even if it only covers a partial percentage of population. This approach addresses both the sustainability aspects of the systems and the whole Programme in the long-term. In *Table 11*, the most striking pros and cons are presented.

**Table 11** Pros and cons of Option A and Option B (at 82% of investment)

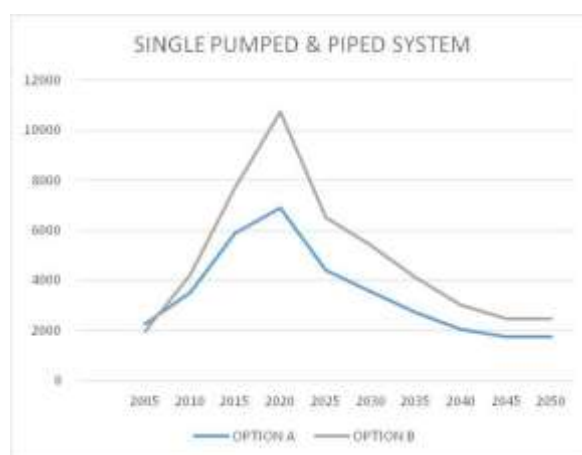
OPTION A		OPTION B (82%)	
Pros	Cons	Pros	Cons
<ul style="list-style-type: none"> <li>- More service in the short-term</li> <li>- No need to be aware of several technical problems</li> </ul>	<ul style="list-style-type: none"> <li>- Mortality of many systems and loss of material</li> <li>- Expensive unit costs</li> </ul>	<ul style="list-style-type: none"> <li>- More service in the long-term</li> <li>- More effective exploitation of resources</li> </ul>	<ul style="list-style-type: none"> <li>- Less population coverage</li> <li>- Need of monitoring water systems over time</li> </ul>

For the different scenarios proposed, the first one establishes decreased unit costs as well as functionality. In this case, a remarkable difference is evident when system rehabilitation is integrated into project implementation (Option B). *Figures 4a* and *4b* show that including rehabilitation results in a higher number of functional systems over time. As an example, by 2020, the systems in service are almost doubled. In parallel, it is noteworthy that the percentage of population covered reaches 89%. Thus, in the first scenario, the option of integrating rehabilitation is preferable to the option of only constructing new water systems (e.g., Option B is preferable to Option A).

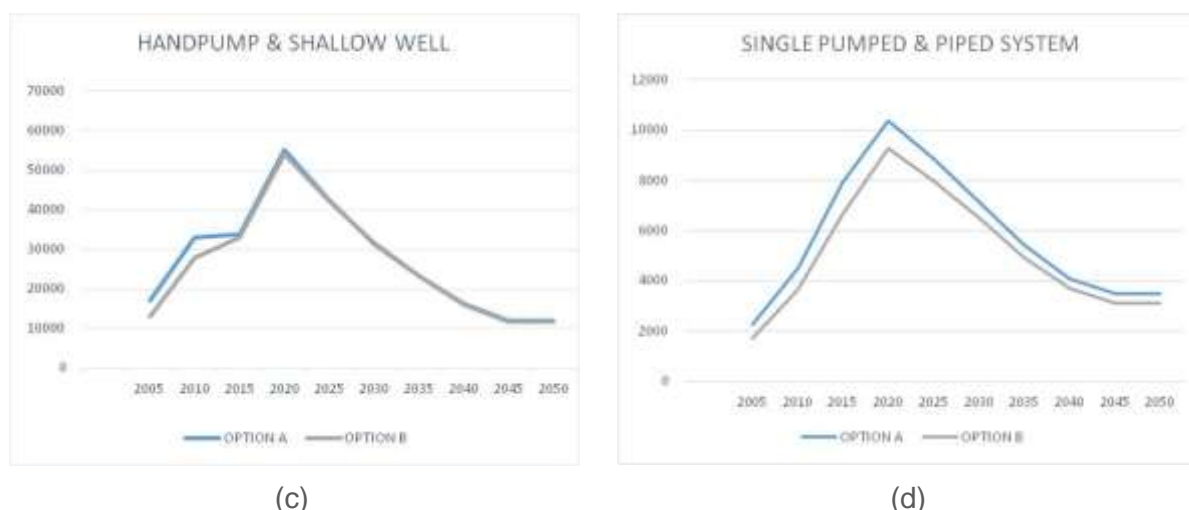
The second scenario is defined by higher unit construction and rehabilitation costs, but also by the associated functionality rate. The results of this scenario are presented in *Figures 4c* and *4d*. In this case, when an Option B approach is applied, only 77% of the population is covered. Taking into account that service rehabilitation does not present a remarkable difference, Option A appears to be more suitable for this second scenario.



(a)



(b)



**Figure 4** Time evolution of functional water systems. Scenario 1 (a,b) and Scenario 2 (c,d).

Comparing both scenarios, and keeping in mind that the total cost of project implementation is constant, one could conclude that, with low functionality rates, integrating the rehabilitation into the planning approach leads to more suitable solution in the long term. However, if the functionality rate is high, even the unit and rehabilitation costs increase, such that considering rehabilitation does not modify project general outcomes. Thus, these factors (unit cost and functionality) are relevant for deciding between both Options. Option A, which is implemented within the NRWSSP, corresponds to the hypothesis of high functionality rates.

On the other hand, as indicated, the real decision-making process might add new variables or aspects to the problem. Considering the selection of the Option B approach as a starting point, a next step might depend on how to implement the Programme and its associated total costs. For this, data regarding estimated population by 2025 is considered, the cost per person covered is calculated, and the mean annual rainfall per region is added (see *Table 12*).

**Table 12** Total cost per person covered and mean annual rainfall, by region

REGION NAME	Total pop. 2025	Total cost	Cost per person covered	Mean annual rainfall (1982 - 2012)
	(thousands of people)	US\$	(US\$/person)	(mm)
Dodoma	3,306	83,055,269	25.12	500 - 750
Iringa	209	20,787,336	99.39	750 - 1,000
Tabora	2,720	107,313,848	39.45	750 - 1,000
Mara	4,226	240,021,582	56.80	750 - 1,000

REGION NAME	Total pop. 2025	Total cost	Cost per person covered	Mean annual rainfall (1982 - 2012)
	(thousands of people)	US\$	(US\$/person)	(mm)
Kilimanjaro	1,673	14,317,593	8.56	500 - 750
Shinyanga	4,891	132,056,873	27.00	1,000 - 1,250
Mbeya	7,292	296,865,306	40.71	750 - 1,000
Morogoro	4,967	164,773,727	33.17	750 - 1,000
Kagera	7,108	143,706,670	20.22	1,500 - 1,750
Mwanza	4,642	108,324,563	23.34	1,000 - 1,250

Taking into account all information available, different alternatives for project implementation might be developed.

- A first alternative could be to give priority to those regions where associated rainfall quantity is lower than an established threshold (e.g. lower than 750 mm.). In this way, coverage of more vulnerable regions, with respect to climatic aspects, will increase.
- A second alternative might be covering, in the first instance, those regions where the costs per person are lower. In this case, it would be possible to reach 100% of coverage in some regions and achieving less than the presented 82% in other regions.
- In contrast, a third alternative could be to give priority to those regions where the cost per person is higher. This would imply making the population with less cost per person to afford those costs.
- If total funding can be increased, a fourth option might be to involve the population and civil society in national coverage improvement. The required funds for covering the entire population could be estimated, as well as the associated costs per person for each region or municipality. As a result, specific and probably different co-funding mechanisms would be established to reach the desired geographical equity objectives, but all of these would be based on a common ground of understanding of the co-funding rules.

Specific calculations for each alternative are not provided, as the aim of this part of the activity is to show different points of view when dealing with decision-making processes. However, each alternative should ideally be linked to a quantitative analysis in order to analyze the suitability, benefits, and drawbacks of each one.

## Solution for Exercise 2

In this exercise, the problem is simplified to two variables ( $C_c$  and  $F_5$ ); by varying them, different values of  $T$  are obtained. The results are detailed in the following table:

	$F_5 = 41$	$F_5 = 51$	$F_5 = 61$	$F_5 = 71$	$F_5 = 81$
$C_c = 4,050$			1,249,518,165		
$C_c = 4,150$			1,280,370,466		
$C_c = 4,250$	1,467,302,250	1,384,446,369	1,311,222,766	1,246,715,606	1,190,009,053
$C_c = 4,350$			1,342,075,067		
$C_c = 4,450$			1,372,927,367		

The linearity of both variables can be verified graphically, plotting total cost against unit cost and functionality rate. Unit costs are clearly linear with the total cost. This is coherent as, considering the same number of systems to be constructed and rehabilitated, the total cost increases or decreases proportionally with the unit costs. On the other hand, the total cost is not linear with functionality. The same amount of reduction or increment of the functionality rate does not represent the same amount of variation of the total cost. This is due to fact that the number of systems to rehabilitate in each period depends on not only the previous time step but on all previous ones.

The values of MRS computation follow. The result expressed with the units are the increment of  $C_c$  per unit of increment of  $F_5$ , maintaining a fixed value for  $T$ .

$$\frac{dT}{dC_c} = \frac{\Delta T}{\Delta C_c} = \frac{1,342,075,067 - 1,280,370,466}{4,350 - 4,150} = 308,523 \quad \text{Incr. } T \text{ per unit of incr. } C_c$$

$$\frac{dT}{dF_5} = \frac{\Delta T}{\Delta F_5} = \frac{1,246,715,606 - 1,384,446,369}{71 - 51} = -6,886,538 \quad \text{Incr. } T \text{ per unit of incr. } F_5$$

$$MRS_{F_5, C_c} = - \left( \frac{dC_c}{dF_5} \right) = - \left( \frac{\frac{dT}{dF_5}}{\frac{dT}{dC_c}} \right) = - \frac{-6,886,538}{308,523} = 22.321 \text{ Incr. } C_c \text{ per unit of incr. } F_5 \text{ with fixed } T$$

For the linear function, the approximation to the derivative is independent of the increment; instead, this is not with the nonlinear relation. In the limit, the value of the incremental difference is equal to the derivative value. A specific analysis considering one-sided increments of descending size illustrates this fact. The concept of the order of approximation can be graphically introduced. Results obtained previously can be compared with ones of centred second-order approximation to derivatives. Recall that incremental approximations to derivatives can be justified using the Taylor's theorem.

Finally, the proposed scenario establishes a specific value for one of the variables ( $F_5 = 85\%$ ). From the MRS expression, it is possible to compute the increment of  $C_c$ , regarding the proposed  $F_5$  increment and specified below:

$$\Delta C_c = MRS_{F_5, C_c} \cdot \Delta F_5 = 22,321 (85-61) = 535.7 \text{ US\$}$$

So, the maximum unit cost that is willing to be paid for increasing the percentage of functionality is:

$$C_c = 4,250 + 535.7 = 4,785.7 \text{ US\$}$$

If the new values of unit cost and functionality are placed in *Annex 2* ("unit costs" and "% functional" tabs), the total cost is basically equal to the initial one.

$$T(4,785.7; 85) = 1,316,693,985 \text{ US\$}$$

Finally, when considering the interaction of several variables, the general expression of the implicit theorem has to be used. For this, the first step is to select the correct number of cost functions to consider. For instance, if the two unit costs ( $C_1$  and  $C_2$ ) and the two functionality rates for the first five-years ( $F_1$  and  $F_2$ ) are considered, and the MRS of costs for functionality rates are of interest ( $MRS_{F, C} = - dC/dF$ ), two constant cost functions are needed. Without more requirements, they could be the investments of the two first five-year periods, or the partial total investments by the two technologies.

However, apart from relating properly the number of variables and functions, the Jacobian matrix of the cost functions with respect to the differentiating variables has to be invertible (technically, at least in a neighbourhood of the point of interest). Therefore, the structure and values of this Jacobian matrix has to be checked for each specific case. Let us consider the



case with the two cost functions equal to the partial costs of the two first five-year periods,  $T_1$  and  $T_2$ , in this case the Jacobian,

$$J_{T,F}(F, C(F)) = \begin{pmatrix} \frac{dT_1}{dF_1} & \frac{dT_1}{dF_2} \\ \frac{dT_2}{dF_1} & \frac{dT_2}{dF_2} \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ \frac{dT_2}{dF_1} & \frac{dT_2}{dF_2} \end{pmatrix},$$

because  $T_1$ , the partial cost of first period, does not depend on the functionality rates (neither  $F_1$  nor  $F_2$ ). Thus, this selection is not useful for computing  $MRS_{F,C}$ . Instead, if the two cost functions are equal to the partial total investments by technology, it is easy to check that the Jacobian is diagonal. The total cost in one technology does not depend on the functionality rate of the other. Thus, this second option is not only possible, but it is an especially good choice from a mathematical point of view; the Jacobian is invertible, and the inverse is diagonal.

### Evaluation Criteria

In order to evaluate this activity, a report will be requested from each group in which the entire activity should be solved.

For the specific assessment of the report, we recommend using the rubrics presented previously (see *Annexes V and VI*), and specifically, for the technical aspects identified within the rubrics.

If this case study is used by a professor of economy, only Exercise 1 should be carried out. As a consequence, the corresponding rubric should be used as well (see Annex V). In contrast, for calculus lessons, we recommend to work on just Exercise 2 and to employ the related rubric (see *Annex VI*).

However, we suggest collaboration between professors of these two subjects, sharing a common context and working on it by using different tools. In this sense, a common rubric should be presented to the students in order to not repeat and evaluate any aspect twice.

Thus, these rubrics represent a possible instrument to facilitate the evaluation of the proposed activities as a whole. As mentioned above, the professor is free to choose an alternative method.

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## ANNEXES

- I. Exercise 1 student version < A.I\_Exercise 1\_student.xlsx >
- II. Exercise 1 professor version < A.II\_Exercise 1\_professor.xlsx >
- III. Exercise 2 student version < A.III\_Exercise 2\_student.xlsx >
- IV. Exercise 1 professor version < A.IV\_Exercise 2\_professor.xlsx >
- V. Evaluation rubric for economy < A.V\_Evaluation\_rubric\_economy.pdf >
- VI. Evaluation rubric for calculus < A.V\_Evaluation\_rubric\_calculus.pdf >



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# Algebra and Large-Scale Dam Assessment: The Case of Merowe Dam in Sudan

David Requejo Castro, Judit Taberna Torres  
and María Isabel García Planas



PHOTO: Merowe Dam inauguration, Sudan. Philip Dhill / EPA



# CASE STUDIES **Algebra and Large-Scale Dam Assessment: The Case of Merowe Dam in Sudan**

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# 2

## ALGEBRA AND LARGE-SCALE DAM ASSESSMENT: THE CASE OF MEROWE DAM IN SUDAN

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## 1. INTRODUCTION

In 2015, world leaders adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals<sup>1</sup> (SDGs). These new global Goals are unique in that they call for action by all countries - low, high and middle-income - to promote prosperity while protecting the planet (United Nations).

Sustainable development has been defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). For sustainable development to be achieved, it is crucial to harmonize three core elements: economic growth, social inclusion, and environmental protection. These elements are interconnected and all are crucial for the well-being of individuals and societies (United Nations).

Dams are often needed to achieve the social and economic dimensions of sustainable development, ideally serving multiple purposes including water supply [SDGs 6.1, 6.4] for agriculture [SDG 2], jobs and industry [SDGs 8, 9], domestic use [SDGs 1, 3, 5, 11], energy generation [SDG 7], and flood and drought protection [SDG 11.5]. Effective reservoir operation for multiple purposes requires the involvement of all sectors and stakeholders, which is supported by Integrated Water Resource Management (IWRM) [SDG 6.5] (UN-Water, 2016).

However, the construction and operation of dams can lead to potential conflict with ecosystems [SDGs 6.6, 15], in different sectors of water use, and between communities [SDG 11]. Further, impacts are often felt in downstream areas and countries. Conflicts can be reduced by ensuring public access to information [SDG 16.10] and by involving all stakeholders in design, planning, and operation [SDG 16.7] through the implementation of IWRM, including at the transboundary level [SDG 6.5]. Technical measures are also needed, such as adequate reservoir operation to ensure sufficient environmental flows to maintain ecosystems and fish migration [SDG 15.5] (UN-Water, 2016).

Through this case study, students will be asked to apply several algebraic contents in order to carry out a simplified design of a dam. The statements mentioned above will also be discussed, focusing on the construction of the Merowe dam, located in Sudan.

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<sup>1</sup> Detailed information regarding the SDGs can be found at <http://www.un.org/sustainabledevelopment>.

### 1.1. DISCIPLINES COVERED

The specific topic covered in this case study falls on Markov chains. This concept is one of the most widely-used applications related to linear algebra, particularly in matrix operations.

Other themes of linear algebra that students that are likewise expected to be more deeply used are modelling, induction hypothesis methods, powers of matrices, diagonalization of linear maps, and the application of these to the resolution of discrete dynamical systems.

Finally, and considering the nature of the class activity, teamwork is promoted in this case study, with the aim of stimulating enriching debates in the classroom.

### 1.2. LEARNING OUTCOMES

After completing this case study, students are expected to be able to:

- Improve their capacity of translating a context statement into algebraic terms;
- Increase their knowledge related to the interdependency of water with other human development aspects;
- Widen their perspective when analysing the complexity of a potential conflict associated to the professional practice of engineering.

### 1.3. ACTIVITIES

In this case study, two activities are requested from the students. In the first, an enrichment debate will be encouraged by reflecting on the importance of water in human development and well-being and on the complexities associated with the construction of a large-scale infrastructure. For this, the context of the Merowe dam built in Sudan is explained. Further, a simplified problem regarding the design of a dam will be worked on the aim to translate it into algebraic terms.

The second activity, designed to be solved out of class, aims to go deeper into the presented problem by applying more advanced algebraic knowledge. In addition, students will be requested to provide an assessment of the results obtained in relation to the contextualization of the case study.

## 2. DESCRIPTION OF THE CONTEXT

In this main part of the case study, we provide a brief description of the complexities that encompassed the construction of the Merowe dam in Sudan. First, we briefly introduce the global perspective of the large-scale dam construction, describing the reasoning for such infrastructures and the potential interest in them. We then focus on Sudan, where the construction of the Merowe dam at the fourth cataract of the Nile River took place. Some relevant factors are provided to allow a simplified sketch of the country to be drawn. Finally, we describe several aspects in detail, such as the global actors involved and the impacts this has had at the environmental, social, and Human Rights levels.

### 2.1. BIG DAMS: A BRIEF GLOBAL PERSPECTIVE

In this section, we present a review of Verhoever (2012b) to provide a global perspective of hydro-infrastructure rationale and potential interests and impacts. Undoubtedly, this is a complex context, where several actors, distinct factors, and geographical regions come into play all together<sup>2</sup>.

“Big dams have long fascinated scientists and politicians alike, sitting at the intersection of water security, modernisation strategies and nationalism. They became popular in low income countries seeking to meet the triple challenge of state-building, nation-building and economic development. General Franco used dams and a powerful water-bureaucracy to re-centralise control over a fragmented, 'backward' nation after the Spanish civil war. Nehru saw dams as the "modern temples of India" lifting hundreds of millions out of poverty through spectacular multiplier effects in industry and irrigated agriculture. And Gamal Abdel Nasser advanced his revolutionary "second Egyptian independence" through the Aswan Dam: Africa's biggest infrastructure project controlled the Nile flood for the first time in history and symbolically catapulted Egypt into the club of advanced nations.

Big dams were believed to magically transform barren wastelands into fertile acreage, elevating the nation and integrating, through irrigation and electrification, the domestic political economy. The World Bank provided the ideological and financial backing for the construction of hundreds of megadams across Latin America, Africa and Asia. Yet from the 1970s onwards, dams as development instruments were increasingly contested. Opponents exposed huge corruption scandals that contributed to the systematic

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<sup>2</sup> *Recommendable lectures for detailed information regarding economic and political background in several dam construction initiatives can be consulted in Dirar et al. (2016) and Verhoever (2012a; 2011).*

overestimation of their benefits and the neglect of their dark side. Paradigmatic cases like the Sardar Sarovar in Western India forced the World Bank to largely withdraw its support for large-scale hydro-infrastructure: the displacement of tens of thousands of people, devastating environmental damage to unique ecosystems, and the undemocratic decision-making surrounding dams triggered a re-think. Many assumed that big dams might be shipped to a museum for 20th century illusions of development - with Western funding drying up, their role in economic growth strategies seemed over.

However, in 2012, dams were staging an impressive comeback, as hundreds of new projects had commenced in the last few years. China, India and Brazil – not coincidentally also the three most important rising powers – are the world's top three dam-builders, each with domestic megaprojects of its own, but also increasingly a proactive role in an emerging global political economy of food and water. Beijing especially was using its formidable technical expertise in hydro-infrastructure and immense foreign reserves to resurrect dam-building overseas: in half of all African countries, from the Sudanese desert and the Ethiopian lowlands to the rivers of Algeria and Gabon, Chinese engineers were involved in the planning, heightening and building of more than 100 dams. The tens of billions of US dollars and thousands of megawatts involved in these projects have so far remained off the radar in the China-Africa debate but are possibly more consequential for the future of the African continent than the exports of oil, copper and other valuable resources.

As the global balance of power shifts eastwards, supply and demand networks are restructured, resulting in tremendous pressures on commodity prices and scarce resources. Dams are therefore no longer merely central to the debate about economic development but also an integral part of water and food security strategies. Food prices especially have spiked, bringing riots in their wake; this has led many to predict that land and water are becoming the world economy's Achilles heel. Emerging powers are seemingly racing to secure the key resources of the future. Big investments by Gulf Arab sovereign wealth funds, purchasing strategies of land by South Korean and Malaysian enterprises and China's involvement in African dam-building cannot be seen in isolation from growing fears about how to ensure water security in the 21<sup>st</sup> century.”

## 2.2. SUDAN AT A GLANCE

Sudan, also known as North Sudan (after south Sudan's independence in 2011 following the Sudanese Civil War; south Sudan is now officially the Republic of the Sudan) is a country in Northern Africa bordered by Egypt to the north, Libya to the northwest, Chad to the west, the Central African Republic to the southwest, South Sudan to the south, and the Red Sea Eritrea and Ethiopia to the east. It is the third largest country in Africa, with an estimated

population of approximately 40 million people (UN-DESA, 2017) and an area of 1,886,068 km<sup>2</sup>. The Nile River divides the country into eastern and western halves. Its predominant religion is Islam.



**Figure 1** Geographical location of Sudan. Sources: [www.wikipedia.org](http://www.wikipedia.org); [www.alamy.com](http://www.alamy.com).

As reflected in the Human Development Report (United Nations Development Programme, 2016), Sudan has a Human Development Index<sup>3</sup> (HDI) of 0.490, which puts it in the group of countries with low HDI, and ranks as the 165 country (out of 185), after Uganda and before Togo and Benin. Although no data are available to calculate other development indices, Sudan does not reflect itself as an unequal country, with a GINI coefficient<sup>4</sup> of 0.35 (where a value of 0 means that everyone has the same income, and a value of 1 means that one person has all the income).

## Social issues

As reflected in the African Economic Outlook (2017), a United Nations Children Fund (UNICEF) report (2014) indicated that more than three million school-age children need have life-sustaining education. A report by the Ministry of Education (2015) found high dropout rates that average 6% and 8% for primary and secondary levels, respectively. The UNICEF report (2014) showed that only 40% of the education sector's needs are funded. These outcomes call for further measures to meet the Sustainable Development Goal (SDG) target 4 on high quality primary and secondary free education by 2030.

<sup>3</sup> Detailed information regarding index construction at <http://hdr.undp.org/en>

<sup>4</sup> More information can be found at <http://data.worldbank.org/indicator/SI.POV.GINI>

The Outlook Report of 2017 continues to emphasise that females made up 49% of the population according to the latest Labour Household Survey (2011). Although Sudan's 2005 Constitution enshrines female emancipation from injustice, promotes gender equality (including in wages), and encourages the role of females in family and public life, gender discrimination is rampant because of the lack of implementation capacity and civil conflicts, as well as cultural and social values. More than 90% of females in the country have been subjected to female genital mutilation; 48% of them are illiterate, as compared to 12% for men; and their rate of participation in the labour force is 14.1% as compared to 38.4% for males. Sudan is among the poorest ten performers on the Gender Inequality Index<sup>5</sup> (GII), with a ranking of 135<sup>th</sup> out of 155 countries in 2014.

### **Environmental issues**

The amount of rainfall increases towards the south. The central and the northern part have extremely dry desert areas, such as the Nubian Desert to the northeast and the Bayuda Desert to the east; in stark contrast, there are swamps and rainforests in the south.

The dry regions are plagued by sandstorms, which can completely block out the sun. In the northern and western semi-desert areas, people rely on the scant rainfall for basic agriculture, and many are nomadic, travelling with their herds of sheep and camels. Nearer to the Nile River, there are well-irrigated farms growing cash crops.

### **Economic issues**

In 2010, Sudan was considered the 17<sup>th</sup> fastest-growing economy in the world, and the rapid development of the country largely from oil profits. Because of the secession of South Sudan, which contained over 80% of Sudan's oilfields, Sudan entered a phase of stagflation (a situation in which the inflation rate is high, the economic growth rate slows, and unemployment remains steadily high). Currently, agricultural production remains Sudan's most-important sector, employing 80% of the workforce and contributing to 39% of the gross domestic product (GDP), yet most farms are rain-fed and thus susceptible to drought. Instability, adverse weather, and low worldwide agricultural prices ensure that much of the population will remain at or below the poverty line for years to come.

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<sup>5</sup> Detailed information regarding index construction at <http://hdr.undp.org/en>



## Governance issues

As explained in Dirar et al. (2015):

“Hydro-infrastructure construction on the Nile is closely related to the consolidation of political and economic power by the ruling elites. The establishment of the Anglo-Egyptian Condominium in 1898 in Sudan was largely hydro-political, as Britain sought to extend its control of the Nile waters to feed its expanding textile industry at home (Waterbury, 1979). ... Immediately after independence in 1956, the elites that enjoyed great economic and political benefits during the years of the Condominium charge of the new nation, replacing the British but maintaining the status quo, albeit with considerable political economic and institutional decay (Harir, 1994).

The year 1989 signalled in the rise to power of Sudan's current Islamist regime known as Harrakat al Islamiyya, with its fundamental project of economic salvation or Al-Injaz. The Injaz regime was propelled by belief that political hegemony was consolidated through economic salvation. As before, the hydro-agricultural base would be the main mobilized resource to achieving this aim. After the downfall of former President, the latter would take the hydro-agricultural ambitions to a new chapter through Sudan's Dam Programme (SDP) and its accompanying Agricultural Revival.

The Injaz maintained the image of an Islamist regime although it shifted the emphasis of legitimizing their seat in power from ideological - radical Islamism, to economic - business partnership. The imperative factor to continued political control of the regime was now in its delivery of economic and developmental success.

The official birthdate of Sudan's Dam Programme can be said to correspond with the establishment of the Dam Implementation Unit (DIU) in 1999. Brought into existence under presidential mandate - specifically for the construction of the Merowe Dam - the DIU is unlike any other state institution in Sudan. ... The nature of the DIU as a governmental institution is unique, and the power that it yields is exceptional. Although it was founded to implement the plans for the Merowe dam, it was promoted into a fully-fledged presidential department. Its jurisdiction extends beyond the purview of dam construction and irrigation into construction works (roads, hospitals, bridges and airports), agricultural development works, electricity provision, preparations and executions of funding activities, and control over its own multi-billion dollar budgets.”

## 2.3. THE MEROWE DAM

### Purpose and construction

“The Merowe hydropower dam was built between the years of 2003–2009 by the National Congress Party of the Islamist Al-Injaz (The Salvation) government in Sudan, and implemented by the Dams Implementation Unit (DIU).

The main purposes for Merowe were hydropower generation, with an operating capacity of 600 MW (total designed capacity 1,200 MW), and irrigation—concurrent with plans for developing centralized agricultural schemes of 300,000 ha. It contains a reservoir of 12.5 km<sup>3</sup>, or about 20% of the Nile's annual flow.

The electrical power generated by the dam is considered and lauded as the greatest imperative by technocratic advocates, as the country's shortages are seen as a great obstacle to development. Current electricity demand across the country greatly outstrips supply. Hydro-electricity provided 50% of electricity in the national grid in the late 1990s and is expanding through new dams and refurbishments of old dam projects. Expanded energy production may not lead to equal distribution, as currently 70% of the available electricity is consumed by the capital, while rural areas are undersupplied (Bosshard and Hildyard, 2005)” (cited from Dirar et al., 2016).

The dam is one aspect of the DIU development plans for Merowe and is in conjuncture with a number of accompanying projects to the region. This includes residential towns, roads and bridges, railways, an airport, and a hospital. However, several studies concluded that the dam has low feasibility (for example, an SWECO finding showed that the feasibility of realizing the agricultural purpose for Merowe were low). Despite its significant environmental, ecological, and social shortcomings, the German company Lahmeyer International provided the project with the technical and generally positive Environmental Impact Assessment (EIA) it required to signal the project's fundraising and construction stages. The positive assessment is suspected to arise from Lahmeyer's secondary role as the primary consultant for the project—posing a clear conflict of interest, and the company has since been implicated in fraud and corruption charges. After many years of obstacles for Merowe, in the form of discouraging studies and difficulty of finding willing financiers, the project finally had the green light of an EIA in 2002, and funding opportunities were provided in the form of domestic oil-export revenue as well as Gulf Arab States and Chinese interest (Dirar et al., 2015).



**Figure 2** Up: Merowe Dam location and infrastructure<sup>6</sup>. Down: Turbine details<sup>7</sup>.

## Global actors

As pointed out by Dirar et al. (2015), the main global players nurturing the Sudanese “development” and dam-building efforts were the Gulf Arab States, Egypt, and China, through financial investment, construction support, and political support. The author states that foreign investment in Sudan was motivated by various global factors, and that the growing involvement of China in the foreign investment-banking sector was coupled with its increased role in the global dam-building industry, which was of particular significance in African states.

The literature review provided by Dirar et al. (2015) states that Arab Gulf Funds supporting Sudan’s hydro-agricultural developments was understood in the global context of rising food prices, concerns with resource limitations, and the desire to secure overseas food production. It follows that hundreds of thousands of fertile lands in North Sudan was being leased to these Arab states under private business agreement. Furthermore, Arab states’ investment was arguably influenced by Sudan’s alliance with Egypt and the promise of an

<sup>6</sup> Sources: [www.wikipedia.org](http://www.wikipedia.org); [english.cntv.cn](http://english.cntv.cn)

<sup>7</sup> Sources: [www.skyscrapercity.com](http://www.skyscrapercity.com); [www.flickr.com](http://www.flickr.com)

Arab-Islamic identity of the nation. Arab political and economic interest was responsible for the financing of Merowe and ten other large hydro-infrastructure projects.

Indeed, Egypt has confirmed that its political support for Sudan's dam initiatives was driven by its perceived national benefits from these projects. Firstly, in light of the emergence of the Nile Basin Initiative (NBI) in 1999, which posed a serious threat to the downstream state's control over upstream use of the flows, Egypt recognized the importance of Sudan as an ally in negotiations. Secondly, population pressures within Egypt and resource limitations to food production had been driving forces behind cooperation with Sudan in the realm of migration, labour, and agriculture. Egypt and Sudan had made arrangements to allow the free flow of labour between the two nations, although in reality, that mainly meant an influx of Egyptian settlers on Sudan's prime irrigated riverside farmland.

### Constructors

Construction began in 2003 after contracts were signed with various international companies for different sections of the dam's construction. As previously mentioned, Lahmeyer International (German) was the main company offering consultancy services throughout the dam's design and implementation phases. The Chinese multinational dam building company, Sinohydro, provided technical input in the form of a large number of highly skilled engineers for the implementation of the Merowe dam. Other international companies involved in Merowe were CMMD (Chinese consortium), tasked with the construction of the accompanying dam structures and related services; Harben Power Engineering (China), responsible for building all the transmission lines and substations; Alstom (French), in charge of manufacturing and installing the dam's 10 turbine units; and ABB (German-Austrian), awarded with the contract for designing and installing the transmission system.

### Funders and financiers

As detailed by the DUI, the summary of investors are shown in *Table 1*:

**Table 1** *Investors of the Merowe Dam. Source: Dams Implementation Unit, 2007.*

INVESTOR	FUND (Million \$US)
Government of Sudan	1,114
Government of China	608
Arab Fund for Economical and Social Development	477
Saudi Fund for Development	215

Abu Dhabi Fund for Development	210
Kuwaiti Fund for Economical Development	200
Sultanate of Oman	106
State of Qatar	15
<b>Total</b>	<b>2,945</b>

## 2.4. ENVIRONMENTAL, SOCIAL AND HUMAN RIGHTS IMPACTS

### Environmental impacts

Sudan's Environmental Protection Act 2001 requires that projects such as the Merowe Dam have an Environmental Impact Assessment (EIA), and that construction should not begin until the EIA has been reviewed and approved by the Government's Higher Council for Environment and Natural Resources (HCENR). Although an EIA was belatedly undertaken for the project by Lahmeyer in 2002, it was short, superficial, and incomplete (Hildyard, 2008). This was confirmed by an independent review of the EIA conducted by the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) in 2006 (Dirar et al., 2016).

The main conclusions of EAWAG's review on the environmental shortcomings of Lahmeyer's EIA of the Merowe Dam include the inadequately assessed risks of sedimentation, greenhouse gas emissions from decomposing organic matter, biodiversity loss and disrupted fish migratory patterns, irrigation (in)feasibility, and deteriorating water quality. It concluded that the trapped sediments (estimated at 130 million tons yearly) would result in a reduction of power-generating capacity of 39% over the next 50 years. Others predict a shorter life span, of 20 years, before total loss of capacity (Verhoeven, 2012a).

The environmental impacts have attracted national concern and studies as well, with a key study by Seif al-Din Hamad (2007), a former minister of irrigation, investigating potential evaporation loss of proposed and constructed dams. The study concluded that if all the planned dams were implemented, Sudan would be faced with serious water shortages for agricultural extension (Seif al-Din Hamad, 2007; cited by Dirar et al., 2016). National experts also express broader environmental concerns of the environmental and ecological irrationality of dams in Sudan, which are threatened by redundancy and short reservoir capacities due to the river's hydrology and high rate of sedimentation.



## Social impacts

The area inundated by the Merowe dam was home to over 60,000 Manasir inhabitants and 10–15,000 inhabitants from Amri and Hamdab communities. Life on the fourth cataract (location of Merowe dam) has traditionally been dominated by small-scale agriculture on the alluvial soils, which border the banks of the Nile. The most important crop to the Manasir, both economically and culturally, is date palm. Date trees are also deeply connected with cultural pride and belongings, and is a symbolic object of cultural reverence. The monetary valuation of date trees is traditionally inconceivable, and various “economic, cultural and social factors result in a practical inconceivability of selling palm trees as real assets among the Manasir” (Haberlah, 2005; cited by Dirar et al., 2016). Prior to the construction of the Merowe dam, the implication of the dam on the life of the Manasir and the issue of displacement and resettlement has been discussed within the communities, with much controversy and differing views. Despite inter-community discussions and debate over the Merowe dam, the people largely were unaware and uncertain as to the details of the extent of the damages and relocation arrangements. Many held hopes that they would not be badly affected and assumed that they would remain in the region by moving to higher grounds (Dirar et al., 2016).

The arrangements for the compensation and resettlement plans and their implementation were conducted by the same authority in charge of the dam itself—the DIU. The official claims of the project authorities and the Lahmeyer EIA was that resettlement offered great opportunities to improve the living standards of the affected populations, and were planned with a development-oriented approach in mind. Many of the Hamdab, Amri, and Manasir people initially welcomed and accepted the dam’s construction. Their initial consent to the project became qualified or changed completely, with time, to the point today that a majority are greatly disappointed.

The Hamdab people were the first group to be resettled in June 2003, as they lived immediately behind the site of the dam. They accepted the resettlement arrangements set out for them and moved approximately 100 km down the river from their homeland and far from its shore. A joint International Rivers Networks and Corner House report concluded that rapidly deteriorating conditions were contributing to worsening poverty (Hildyard, 2008). Unfair compensation for lost assets and attempts of the project authorities to dwarf the people’s entitlements, combined with conditions of poor soil quality and failing agricultural production, reportedly increased the poverty rate from 10% to 65% in the period of two years. The agricultural projects resettled farmers engaged in at the new site failed repeatedly, due to failing irrigation schemes. Water shortages continued to plague the resettlement site in 2014 (Dirar et al., 2016).

Based on the experiences of deteriorating conditions the Hamdab people faced, the Amri and Manasir groups were more cautious in accepting the arrangements set up for them by the dam authorities. Whilst some of the people from these groups accepted resettlement, a large proportion resisted and demanded to alternatively be resettled close to the reservoir's shoreline. Those that declined the official plans opted for an option proposed by their representative committees known as the "local option". A few days after the decisions were released, the head of the DIU appeared on television making a mockery of the decisions and indicating the weak chances of the successful implementation of the "local option". Frustrated by lack of recognition of their demands and the futility of formal bureaucratic engagement, the affected people strengthened their resistance through peaceful, and later, armed struggles to realize their aims.

In brief, the compensation and resettlement experience was characterized by a lack of transparency and consultation of affected people, and a shocking disregard by the DIU of the formal negotiations between the Committees of the dam affected peoples (DAPs) and State officials and ministries. In a manner similar to the execution of the EIA, the absolute power granted the DIU by the presidency ensured the outcome.

### **Human Rights impacts**

The communities affected by the Merowe project have consistently stated that they are not opposed to the dam on principle but that they wish to see their rights to just resettlement and compensation respected. Peaceful protests to achieve these ends, however, have repeatedly been met with force. Critics of the project have also been subject to arbitrary arrests, intimidation, and torture (Hildyard, 2008). The most severe event took place in 2006, where a protest of the Amri population resulted in the death of three citizens and injury to more than 50<sup>8</sup>.

Although the companies have been informed of such abuses, they have (with the exception of ABB) either stood resolutely on the sidelines, refusing to intervene, or have sided with the authorities. Responding to the April 2006 shootings at Amri, for example, the China International Water and Electric Corporation issued a statement denying that any disturbances had taken place. Lahmeyer acknowledged that shootings had taken place but placed the blame on "a group of landless protestors" who attacked officials who were attempting to deal with compensation disputes. Alstom remained silent on the massacre. Only ABB acted, expressing its concern directly to the Sudanese authorities, calling for "a full inquiry and for the results to be made public".

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<sup>8</sup> More information related to reported violent events can be found in Hildyard (2008).

### 3. CLASS ACTIVITY

The proposed class activity aims to encourage a debate around the context that involved the construction of the Merowe dam. In so doing, several questions will be put into play as a starting point. In this sense, it is recommendable to provide the students with that material in advance. On the other hand, a simplified problem associated to the design of a dam will be proposed to the students in order to learn how to translate it into algebraic terms. This is especially relevant, as it will provide the base for carrying out the homework activity.

This class activity is divided in two sections or blocks, with a total duration of about two and a half hours. As far as the methodology, we propose that students work in small groups (i.e. 3 to 4 people); further details are given in each block of the activity.

#### **Class activity: Block I**

The first part of the class activity, programmed for one and a half hours work, proposes to reflect on several of the aspects introduced in this case study. For this, a group discussion is encouraged to take place in every group after the first half (at 45 minutes). To conclude the activity, a general debate of 45 minutes is recommended to put all points of view together.

First, a simple question is asked to the students:

- Which is the aspect (from all the circumstances, impacts, and facts that you have been presented) that most attracted your attention?

Second, the following questions are presented for encouraging further debate:

- If a company supplies turbines for a hydroelectric dam, does it have a responsibility, legal or moral, to ensure that the dam's environmental and social impacts are minimized?
- Or do its ethical policies and legal obligations extend only to ensuring that the manufacture of the turbine is environmentally sound and without human rights impacts?
- What about other actors involved in the dam or any other project?
- For example, banks and financial institutions - do they have a duty to ensure that the money they provide for projects does not facilitate adverse environmental impacts and human rights abuses?



Finally, a brief analysis of the direct and indirect impacts (positive or negative) associated with dam construction is requested from the students. For this, *Table 1* should be filled out. As stated, this analysis must be done considering the social, environmental, and economic dimensions.

**Table 1** *Proposed dimensions on which to base the discussion about potential direct and indirect impacts of a dam construction.*

DIMENSION	DIRECT IMPACTS	INDIRECT IMPACTS
Social		
Environment		
Economy		

### Class activity: Block II

This second part will take another hour of work. We suggest maintaining the same working groups. For this block, we propose using the following example:

The Government of Sudan plans to build another reservoir to regulate the basin of one of its rivers to meet water requirements for irrigation. The maximum expected dam capacity will be  $5,000,000 \text{ m}^3$  ( $5 \text{ km}^3$ ), or abbreviated, 5 units of water (1 unit of water =  $1,000,000 \text{ m}^3$ ). The Merowe dam contains a reservoir of  $12.5 \text{ km}^3$  (20% of the Nile's annual flow). Before proceeding to construction, the Government would like to have some idea about the effectiveness of the dam over the long term. In so doing, a study analyzed the yearly volumes of water provided by the river and has found that they can be approximated using the following distribution of discrete probability:

Yearly contribution in units of water	2	3	4	5	6
Probability	0.2	0.4	0.2	0.1	0.1

The Government is considering the possibility of making irrigation contracts that will require the consumption of 2 units of water per year. However, in order to maintain water quality standards for other uses, 1 unit of water per year must be kept constantly. Therefore, the yearly goal will be to let out 3 units of water. If the state of the reservoir (level of the reservoir) plus the water intake of the river is less than this amount, less quantity of water must be let out, thus affecting the irrigation schemes. If the reservoir is full, any excess will be taken through the spillways (surplus water dumps). The minimum permitted level of the reservoir (minimum state) may not be less than 1 water unit.

Students should now model the problem using a discrete linear dynamical system—that is to say, through the use of a matrix equation of type  $p(k+1) = A \cdot p(k)$ , describing the probable yearly transition of the units of water. As the whole solution of the problem will be left for the homework activity, only the solution for the case of having one unit of water should be presented in Block II.

### 3.1. SOLUTION AND EVALUATION CRITERIA

#### Class activity: Block I

There is no a specific solution for this activity, as it is an open-answer one. The main idea is to give students the chance to present and defend their arguments. This statement is more related to the first and second set of questions.

On the other hand, students have been provided with a brief guide of potential impacts of a dam construction. Although a deeper analysis could be done, the objective is to offer the professor a tool to facilitate the debate as the moderator (in the case that there is a lack of participation).

DIMENSION	DIRECT IMPACTS	INDIRECT IMPACTS
Social	<ul style="list-style-type: none"> <li>- Water supply for domestic purposes</li> <li>- Displacement of people</li> <li>- Disappointment of citizens</li> </ul>	<ul style="list-style-type: none"> <li>- Improving human health and well-being</li> <li>- Losses of personal roots; change in life dynamics</li> <li>- Dissatisfaction with political system; potential violent conflicts</li> </ul>
Environment	<ul style="list-style-type: none"> <li>- Flood and drought protection for humans</li> <li>- Potential ecosystem damage</li> <li>- Clean energy generation</li> </ul>	<ul style="list-style-type: none"> <li>- Alteration of environment initial state</li> <li>- Increasing the possibility of a natural point of no return</li> <li>- Reducing GHG (greenhouse gases) emissions</li> </ul>
Economy	<ul style="list-style-type: none"> <li>- Water supply for agriculture and industry</li> <li>- Job creation</li> <li>- Energy provision</li> <li>- Mobilizing economic market</li> </ul>	<ul style="list-style-type: none"> <li>- Improving economic activity; ensuring food security</li> <li>- Increasing people's power purchase</li> <li>- Improving human well-being and promoting economic growth; promoting transboundary businesses</li> <li>- Business development; potential corruption</li> </ul>

**Class activity: Block II**

Let's call  $k$  = years

$p_i(k)$ , where  $i = 1; 2; 3; 4; 5$ , it is the probability of the dam to have  $i$  units of water in the year  $k$ .

The matrix  $A = (p_{ij})$  where  $p_{ij}$  denotes the probability that having  $j$  units in the year  $k$ , there are  $i$  units in the year  $k + 1$ .

In order to calculate  $p_{ij}$  (when  $j = 1$ ), the starting point is set as the point at which the dam's level is equal to 1 unit of water. Then, and considering the possible river contributions, the different states of the dam, in terms of capacity, are calculated. Finally, and taking into account the conditions established in this activity (minimum and maximum levels, and quantity for irrigation), the final level of the dam after water provision can be obtained. The following table represents this line of reasoning.

Units in year $k$	Water entrance	Probability	Dam state after water entrance	Water provision	Units in year $k + 1$
1	2	0.2	3	2	1
	3	0.4	4	3	1
	4	0.2	5	3	2
	5	0.1	6	3	3
	6	0.1	7	3	4
Result: $p_{11} = (0.2 \times 1) + (0.4 \times 1) = 0.6$					

Thus, as evident from the previous table, when the initial capacity is 1 unit of water (year  $k$ ), the final level (year  $k + 1$ ) will be equal to 1 unit when the water entrance is 2 or 3 units of water. Thus, the dam's probability to reach 1 unit capacity is 60% (0.6), which corresponds to the probability sum of the water entrance of 2 or 3 units of water.

Units in year k	Water entrance	Probability	Dam state after water entrance	Water provision	Units in year k + 1
2	2	0.2	4	3	1
	3	0.4	5	3	2
	4	0.2	6	3	3
	5	0.1	7	3	4
	6	0.1	8	3	5
Result: $p_{12} = 0.2 \times 1 = 0.2$					

Units in year k	Water entrance	Probability	Dam state after water entrance	Water provision	Units in year k + 1
3	2	0.2	5	3	2
	3	0.4	6	3	3
	4	0.2	7	3	4
	5	0.1	8	3	5
	6	0.1	9	4	5
Result: $p_{13} = 0$					

For the results, when i is equal to 4 and 5, it will be equal to zero as well. In this sense, the results obtained represent the first row of the 5×5 matrix that it will be obtained (0.6; 0.2; 0; 0; 0).

### Evaluation criteria

In order to provide an objective and transparent evaluation system for students, we propose to use a rubric (see *Annex I*). In this sense, the rubric shows: i) the knowledge that students are expected to acquire; and ii) the criteria used to evaluate the content of the answers associated with the proposed activities.

To use this rubric, first provide it to the students in order to inform them how they will be evaluated. Giving the students some guidance may be necessary to allow them to focus on the specific goals (in terms of answers).

To facilitate evaluation, each group must submit (or give in paper format) the answers to the professor at the end of the class. These answers will be evaluated based on the criteria of the rubric. However, the teacher is free to choose an alternative evaluation method that might be considered more appropriate.

#### 4. HOMEWORK ACTIVITY

As for the previous activity, homework is recommended to be done in small groups (i.e. 3 or 4 students). However, the teacher can make the final decision. In total, we estimate that the whole activity will need an effort of 10 hours work.

The starting point of this activity is the problem presentation introduced in the class activity second block. Now, students are requested to work on the following tasks:

- Obtain the remaining terms  $p_{ij}$  and specify how this process was carried out. In addition, the resulting system should be presented;
- Assuming that the initial situation of the dam is related to a level of 3 units of water, what is the probability to be at the minimum level two years later?
- Study the asymptotic behaviour of the system. Is the dam sustainable?
- Provide an assessment in the context of the problem, in terms of results and knowledge acquired.

##### 4.1. SOLUTION AND EVALUATION CRITERIA

Obtain the remaining terms  $p_{ij}$  and specify how this process was carried out

The problem exposes a set of conditions that should be presented along with all calculations and procedures effected. Thus, it is necessary to consider that the maximum capacity of the reservoir is 5 units of water, and that the minimum level admitted is 1 unit of water (with 1 unit = 1,000,000 m<sup>3</sup>). Thus, if the reservoir level plus the yearly contribution from the river is lower than 3 units, a lower quantity of water should be extracted, as the minimum level must be maintained. This fact will produce a deficiency in the irrigation scheme.

The initial level of water can be 1, 2, 3, 4, or 5 units (first column of the following tables). In each one of the cases, there is a contribution of river water of 2, 3, 4, 5 or 6 units, with the

probability stated in the problem (second and third columns, respectively). The state of the reservoir corresponds to the sum of the initial state and the yearly river contribution (fourth column). Now, 3 units are extracted from each case, such that the final level of the reservoir corresponds to the state of the reservoir minus 3 units (fifth column).

At this point, it is necessary to be careful. No just any value can be accepted for the final level of the reservoir, as the minimal restrictions must be respected. Thus, the final value can only be 1, 2, 3, 4, or 5 units of water (as the minimum level is 1 unit, and the maximum, 5). The last column of the table ("observations") represents whether or not the final dam level is acceptable.

Thus, when the reservoir state is  $\leq 3$ , the final level will be 1; in other words, the irrigation needs will not be satisfied. On the other hand, when the reservoir state is  $\geq 9$  units, the final level will be 5, as that is the maximum capacity. More units than strictly necessary will be extracted, and therefore excessive units of water will be poured out. To calculate the number of units of water that are excessive, it is necessary to subtract 8 units (5 corresponding to the capacity of the reservoir, and 3 corresponding to the aim of the problem) to the state of the reservoir. With all these considerations in mind, the associated tables are presented below:

Units year k	Water entrance	Probability	Dam state	Water provision	Units year k + 1	Observations
1	2	0.2	3	2	1	Needs not met
	3	0.4	4	3	1	Correct
	4	0.2	5	3	2	Correct
	5	0.1	6	3	3	Correct
	6	0.1	7	3	4	Correct

Units year k	Water entrance	Probability	Dam state	Water provision	Units year k + 1	Observations
2	2	0.2	4	3	1	Correct
	3	0.4	5	3	1	Correct
	4	0.2	6	3	2	Correct
	5	0.1	7	3	3	Correct
	6	0.1	8	3	4	Correct

Units year k	Water entrance	Probability	Dam state	Water provision	Units year k + 1	Observations
3	2	0.2	5	3	2	Correct
	3	0.4	6	3	3	Correct
	4	0.2	7	3	4	Correct
	5	0.1	8	3	5	Correct
	6	0.1	9	4	5	Excess through spillways

Units year k	Water entrance	Probability	Dam state	Water provision	Units year k + 1	Observations
4	2	0.2	6	3	3	Correct
	3	0.4	7	3	4	Correct
	4	0.2	8	3	5	Correct
	5	0.1	9	4	5	Excess through spillways
	6	0.1	10	5	5	Excess through spillways

Units year k	Water entrance	Probability	Dam state	Water provision	Units year k + 1	Observations
5	2	0.2	7	3	4	Correct
	3	0.4	8	3	5	Correct
	4	0.2	9	4	5	Excess through spillways
	5	0.1	10	5	5	Excess through spillways
	6	0.1	11	6	5	Excess through spillways

Once the problem is analyzed, it will be defined using the matrix equation of  $p(k+1) = A \cdot p(k)$ .

Let's define  $k$  as the years passed,  $p(k)$  as the probability of the initial state of the reservoir, and  $p(k+1)$  as the probability of the reservoir state a year later. Additionally,  $A$  is defined as the matrix of transition obtained by using the chain of Markov.

To find the  $A$  matrix, it is necessary to focus on the tables generated previously, and specifically, the columns related to the initial level ( $k$ ) and the final level ( $k + 1$ ) of the reservoir, and the probability of river contribution.

Each row of the  $A$  matrix refers to the final level of the reservoir, and each column expresses the initial level. As there are 5 initial states and 5 distinct final states, the  $A$  matrix will have the dimension  $5 \times 5$ . Each element of the matrix indicates the probability of beginning with a determinate initial level of water and finishing with another. In order to find each element, the volume contributed by the river should be analyzed. For example, to focus on the first row, which is associated with a final level of 1 unit of water, the following should be done:

In the first-year table, examine the column of the final levels (Units year  $k + 1$ ) to find the value of 1 unit; note that river contributions of either 2 or 3 units (water entrance) gives a final level of 1. The probability of finishing the year with 1 unit of water in the reservoir is 20% if the river feeds in 2 units of water, and 40% if the river feeds in 3 units of water. Therefore, there is a 60% of probability to begin with 1 unit of water and finish with 1 unit (e.g., if the probabilities 20% + 40% are summed). This value corresponds to the element of the first row and the first column of the  $A$  matrix.

For the second term of the  $A$  matrix, the first row will correspond to the total probability of having an initial unit of water level of 2, and a final level of 1. This probability is 20%, as it is only achieved when the contribution is 2 units of water. Finally, the remaining terms of the first row correspond to 0, since there is no situation in which the reservoir has an initial level of 3, 4, or 5 units of water and finishes with a final level of only 1 unit of water (zero probability). To complete all the elements of the matrix, the procedure should be repeated for each value of the initial and final levels. For this, the following equations should be applied:

- $p_1(k+1) = 0.6 \cdot p_1(k) + 0.2 \cdot p_2(k) + 0 \cdot p_3(k) + 0 \cdot p_4(k) + 0 \cdot p_5(k)$
- $p_2(k+1) = 0.2 \cdot p_1(k) + 0.4 \cdot p_2(k) + 0.2 \cdot p_3(k) + 0 \cdot p_4(k) + 0 \cdot p_5(k)$
- $p_3(k+1) = 0.1 \cdot p_1(k) + 0.2 \cdot p_2(k) + 0.4 \cdot p_3(k) + 0.2 \cdot p_4(k) + 0 \cdot p_5(k)$
- $p_4(k+1) = 0.1 \cdot p_1(k) + 0.1 \cdot p_2(k) + 0.2 \cdot p_3(k) + 0.4 \cdot p_4(k) + 0.2 \cdot p_5(k)$
- $p_5(k+1) = 0 \cdot p_1(k) + 0.1 \cdot p_2(k) + 0.2 \cdot p_3(k) + 0.4 \cdot p_4(k) + 0.8 \cdot p_5(k)$



It should be mentioned that  $p_1(k)$  expresses the probability of initially having 1 unit of water;  $p_2(k)$ , the probability of having 2; and so forth. The result could be represented as follows:

$$A = \begin{pmatrix} 0.6 & 0.2 & 0 & 0 & 0 \\ 0.2 & 0.4 & 0.2 & 0 & 0 \\ 0.1 & 0.2 & 0.4 & 0.2 & 0 \\ 0.1 & 0.1 & 0.2 & 0.4 & 0.2 \\ 0 & 0.1 & 0.2 & 0.4 & 0.8 \end{pmatrix}$$

$$\begin{pmatrix} p_1(k+1) \\ p_2(k+1) \\ p_3(k+1) \\ p_4(k+1) \\ p_5(k+1) \end{pmatrix} = \begin{pmatrix} 0.6 & 0.2 & 0 & 0 & 0 \\ 0.2 & 0.4 & 0.2 & 0 & 0 \\ 0.1 & 0.2 & 0.4 & 0.2 & 0 \\ 0.1 & 0.1 & 0.2 & 0.4 & 0.2 \\ 0 & 0.1 & 0.2 & 0.4 & 0.8 \end{pmatrix} \begin{pmatrix} p_1(k) \\ p_2(k) \\ p_3(k) \\ p_4(k) \\ p_5(k) \end{pmatrix}$$

Probability of having a minimum level 2 years later (assuming an initial capacity of 3 units of water)

From the A matrix obtained previously, it is possible to express  $p(k)$  as a function of  $p(0)$ , that is, the general term of the vector succession defined by recurrence.

Considering the relation between the initial condition  $p(0)$  and the first year  $p(0+1)$ , which is  $p(1)$ , the resultant matrix would be:

$$p(1) = A \cdot p(0)$$

Then, considering the relation between the first and second years, the following is obtained:

$$p(1+1) = A \cdot p(1) \text{ or } p(2) = A \cdot p(1)$$

So,

$$p(2) = A \cdot p(1) = A \cdot [A \cdot p(0)] = A^2 \cdot p(0)$$

Likewise, the relation between the remaining years can be found:

$$p(3) = A \cdot p(2) = A \cdot A^2 \cdot p(0) = A^3 \cdot p(0)$$

Therefore, it is possible to deduce the general form of  $p(k)$  as a function of  $p(0)$ :

$$p(k) = A^k \cdot p(0)$$

To prove the veracity of this expression, Markov chain is applied.

$$p(k+1) = A^{k+1} \cdot p(0) = A^k \cdot A \cdot p(0) = A \cdot p(k)$$

Replacing  $A^k \cdot p(0) = p(k)$ , it is indeed seen that  $p(k+1) = A \cdot p(k)$ , which demonstrates the expression on hand.

To solve this, we can observe that  $p(2) = A \cdot p(1) = A(A \cdot p(0)) = A^2 \cdot p(0)$ ; then:

$$A^2 = \begin{pmatrix} 0.6 & 0.2 & 0 & 0 & 0 \\ 0.2 & 0.4 & 0.2 & 0 & 0 \\ 0.1 & 0.2 & 0.4 & 0.2 & 0 \\ 0.1 & 0.1 & 0.2 & 0.4 & 0.2 \\ 0 & 0.1 & 0.2 & 0.4 & 0.8 \end{pmatrix}^2 = \begin{pmatrix} 0.6 & 0.2 & 0 & 0 & 0 \\ 0.2 & 0.4 & 0.2 & 0 & 0 \\ 0.1 & 0.2 & 0.4 & 0.2 & 0 \\ 0.1 & 0.1 & 0.2 & 0.4 & 0.2 \\ 0 & 0.1 & 0.2 & 0.4 & 0.8 \end{pmatrix}$$

$$p(0) = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

$$A^2 p(0) = \begin{pmatrix} 0.04 \\ 0.16 \\ 0.24 \\ 0.22 \\ 0.34 \end{pmatrix}$$

The obtained result permits us to conclude that there is a 4% probability of reaching the minimum level according to the initial conditions. On the other hand, there is a higher probability of achieving a final level of 3, 4, or 5 units of water than a low or minimum level (2 or 1 units, respectively). Specifically, there is an 80% probability of reaching a high level of the dam after two years, taking into account the initial condition of 3 units of water.

#### Asymptotic behaviour of the system (dam sustainability)

Asymptotic behaviour refers to the tendency of the water amount stored. In order to analyze the evolution of the water level, the limit  $A_k$  should be calculated.

For this, the eigenvalues of matrix  $A$  are calculated:

$$1.0000, 0.7685, 0.4553, 0.1129, 0.2633$$

Taking into account that there is a unique eigenvalue of module 1, and that the rest have a module strictly less than 1, the normalized eigenvector  $v_1$  (corresponding to eigenvalue 1) needs to be obtained.

$$v_1 = (0.0194, 0.0388, 0.0971, 0.2427, 0.6020)$$

$$\text{Then, } \lim_k \cdot A^k = v_1$$

Unlike stability, the concept of sustainability is not defined mathematically. In this sense, each student should assess whether the probability of the dam's water level makes it sustainable, and they should weigh this together with all other aspects.

### Results assessment

Some aspects to be considered are presented here for the obtained results. While numerical results should be presented by the students, the assessment associated with the context is an open-answer. Ideally, students should link the information presented in this case study with the numerical results.

First, it is possible to affirm that the calculations carried out show that, regardless of the initial situation of the dam, the level of water to which it tends will be the same. If these data (first year) is compared with that obtained in the third year, it should be evident that the higher the initial level of the dam is, the greater the probability of getting higher levels.

Further, it should be affirmed that there is a 94% probability of reaching an appropriate level (of 3, 4, or 5 units of water). Specifically, there is a 84% probability associated with ending with 4 or 5 units of water. From these results, there is a 60% probability of reaching the maximum level allowed. On the other hand, the probability that the dam contains only 1 or 2 units of water is 1.94% and 3.88%, respectively. Thus, the probability of reaching minimum levels is less than 6%.

From these results, we can conclude that the dam level will be always above the minimum required, and that it will not suffer large fluctuations. Thus, the construction seems to be viable and to satisfy the irrigation scheme designed (as well as the consequent energy generation). Therefore, the impacts in local economy should be positive in terms of food security, economic activity, human well-being, and health. This result would be reached if the initial conditions are accomplished - in other words, if the probabilities related to the dam water contributions take place. Thus, an appropriate and rigorous study in this sense is relevant for the design of the project. Otherwise, a different region with, for example, different rain patterns (water contribution) could be selected.

Likewise, the tendency associated to the probability to reach the maximum level represents a risk of overflowing the dam. This is translated into the possibility to affect different areas and activities of the citizens, if it is not properly considered. In the same way, ecosystems would experience several negative impacts, both downstream and upstream.

Controlling the river flow of the Nile is a technical challenge with positive and negative impacts. Special attention should be given to further ones. If social losses are expected, trade-offs should be negotiated with the people involved. There is no doubt that this is a difficult process, but dialogue and negotiation, rather than imposition, should be the way. Similarly, a strategy of transparency should be applied to facilitate the involvement of all stakeholders. The positive impacts of encouraging participation can increase not only institutional trust but also build a more cohesive society, if seen from a long-term perspective. People's life style, cultural believes, traditions, and life environments are affected when constructing large-scale infrastructures like the studied dam. Thus, it should be mandatory, and even regularized, to integrate these aspects when implementing such projects.

### **Evaluation criteria**

In order to evaluate this activity, a report will be requested from each group, in which the entire activity should be solved.

For the specific assessment of the report, we recommend using the rubric presented previously (see *Annex I*), and specifically, the technical aspects identified within the rubric. However, and depending on the responses of the students, aspects other than those included in the rubric should be considered. Thus, the rubric represents a possible instrument to facilitate the evaluation of the proposed activities as a whole. As mentioned above, the professor is free to choose an alternative method.

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# Exploring the Use of Recycled Aggregates in Concrete Mix Proportion: an Alternative for Haiti?

David Requejo Castro and Miren Etxeberria

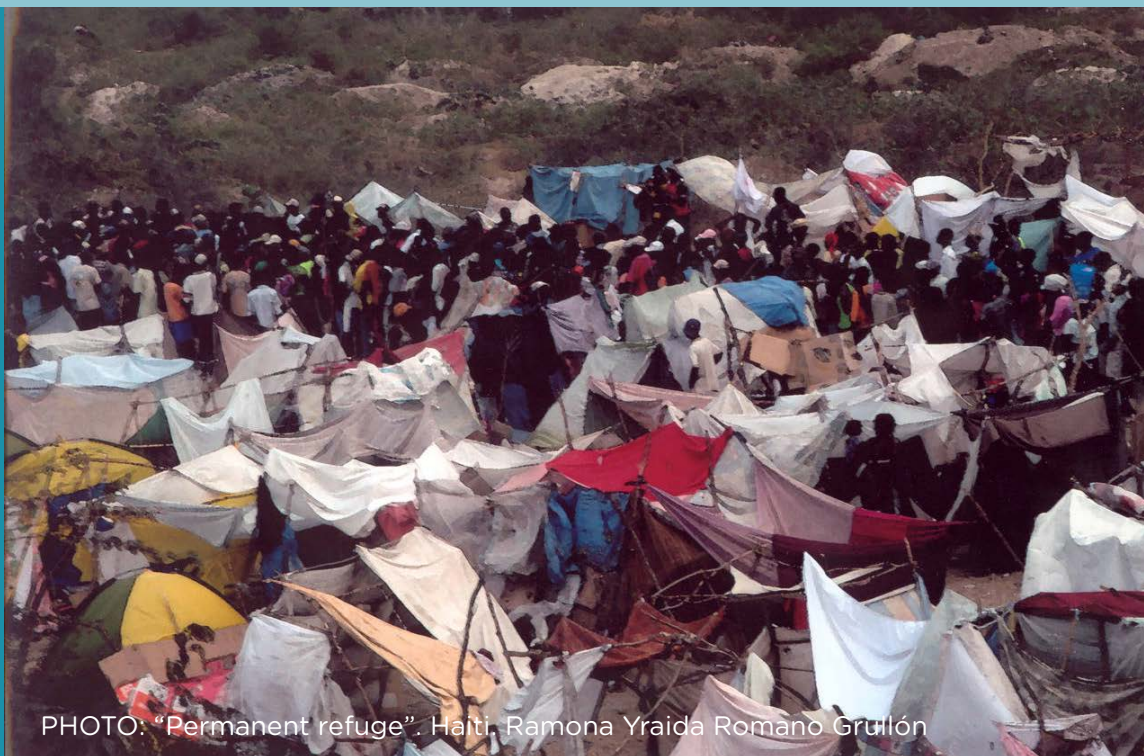


PHOTO: "Permanent refuge". Haiti, Ramona Yraida Romano Grullón





# CASE STUDIES Exploring the Use of Recycled Aggregates in Concrete Mix Proportion: an Alternative for Haiti?

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# 3

## EXPLORING THE USE OF RECYCLED AGGREGATES IN CONCRETE MIX PROPORTION: AN ALTERNATIVE FOR HAITI?

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## 1. INTRODUCTION

In 2015, world leaders adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals<sup>1</sup> (SDGs). These new global Goals are unique in that they call for action by all countries—low, middle, and high income—to promote prosperity while protecting the planet. They recognize that ending poverty must go hand-in-hand with strategies that build economic growth and address a range of social needs, including education, health, social protection, and job opportunities, while tackling climate change and environmental protection (United Nations).

Specifically, Goal 11 sets out to “make cities inclusive, safe, resilient, and sustainable”. In doing so, this goal proposes to focus on 10 Targets<sup>2</sup>. Among these, the fifth Target (11.5) reads “by 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations”.

A growing international focus on resilience is a core agenda item for cities today. The increase in severe weather events and natural disasters has highlighted the need for cities to augment their ability to withstand the disaster risks they may face, and to mitigate and respond to such risks in ways that minimize the impact of severe weather events and natural disasters on the social, environmental, and economic infrastructure of the city (United Nations Human Settlements Programme, 2016).

With this in mind, we would like to introduce the context of Haiti, and in particular, that of the devastating effects of the 2010 earthquake that measured 7.0 on the Richter scale in Haiti. With 1.2 million people left homeless, this natural disaster is considered one of the largest humanitarian catastrophes in history. Furthermore, it is a clear example that encourages us to achieve the Target 11.5.

In this case study, students will be invited to think and discuss about the complexities of such a context. In addition, technical aspects regarding concrete dosage will be worked on, and specifically, those related to the use of recycling aggregates as a potential alternative for post-disaster situations.

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<sup>1</sup> Detailed information regarding the SDGs can be consulted at <http://www.un.org/sustainabledevelopment>.

<sup>2</sup> A description of the Goal 11 Targets can be found at <http://www.un.org/sustainabledevelopment/cities>.

### 1.1. DISCIPLINES COVERED

Basically, this case study covers the discipline of construction materials. Specifically, it focuses on the use of conventional and recycled aggregates for concrete elaboration. Our objective is to go deeper into several aspects related to the construction of the most popular building materials in the world.

In addition to this, we address cooperation for development-related issues as well. Finally, as the proposed activities are carried out in small groups, this case study should promote teamwork and ultimately stimulate a general debate in the classroom.

### 1.2. LEARNING OUTCOMES

As a result of this case study, students are expected to be able to:

- Know the indicators employed, at a global level, to measure important aspects such as human development, gender equality, and poverty;
- Analyse critically those indicators by considering their direct and indirect impacts;
- Understand the complexity of a post-disaster context;
- Apply the methodology related to concrete dosing using both raw and recycled aggregates.

### 1.3. ACTIVITIES

After the description of the context is provided to the students, the class activity will encourage them to think of the complexities associated with a post-disaster situation. Students will also be asked to reflect on the different impacts related to several aspects. In addition, they will be in the position to take some decisions and then defend their arguments.

Furthermore, technical work will also be required from the class. First, students will work on the concrete dosage definition for both using raw and recycled aggregates. Second, they will be asked to elaborate a proposal for knowledge transfer to less-trained practitioners.

## 2. DESCRIPTION OF THE CONTEXT

In this section, we provide a detailed contextualization of Haiti with the aim of bringing students closer to understanding a situation of post-disaster. We introduce relevant information related to the country in order to allow the student to understand the situation prior to the catastrophic 2010 earthquake. For this, social, environmental, economic, and governance aspects are briefly explained. In parallel, we also present the impacts of the disaster on these aspects. Finally, we give an overview of the housing sector in order to carry out, in conjunction with the previous information, the proposed activities.

### 2.1. HAITI AT A GLANCE

Haiti (officially, the Republic of Haiti) is a country located on the island of Hispaniola in the Greater Antilles archipelago of the Caribbean Sea. It occupies the western three-eighths of the island, which it shares with the Dominican Republic. Haiti is 27,750 square kilometres in size and has an estimated 10.6 million people (382 inhab/km<sup>2</sup>), making it the most populous country in the Caribbean Community (CARICOM) and the second-most populous country in the Caribbean as a whole.

As reflected in the Human Development Report (United Nations Development Programme, 2016), Haiti is characterised by a Human Development Index<sup>3</sup> (HDI) of 0.493, which puts it in the group of countries with low HDI; it ranks 163 (out of 185 countries) and is below Senegal and above Uganda and Sudan. The Adjusted HDI (IHDI), which reflects disparities between the population in income, health, and education, is 0.298, meaning 40% less than the corresponding HDI. This demonstrates that Haiti is one of the most unequal countries, with a GINI coefficient<sup>4</sup> of 0.61 (where a value of 0 means that everyone has the same income, and a value of 1 means that one person has all the income).

To meet the challenges of development, Haiti adopted a National Strategy Paper in 2007 on Growth and Poverty Reduction (DSNCRP) for a three-year period (2008–2010). The long-term objective of the DSNCRP was to get Haiti out of the category of less-developed countries, appreciably by improving the population's living conditions and reducing poverty (United Nations Development Programme, 2013). In addition to this already enormous challenge, Haiti has been forced to deal with several natural disasters, such as the 2010 earthquake that brought international attention to this country.

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<sup>3</sup> Detailed information regarding index construction at <http://hdr.undp.org/en>

<sup>4</sup> More information can be found at <http://data.worldbank.org/indicator/SI.POV.GINI>

## 2.2. NATURAL DISASTERS

After 240 years of inactivity, the Enriquillo Plantain Garden Fault ruptured on 12 January 2010 at 4:53 pm local time, resulting in an earthquake that measured 7.0 on the Richter scale in the vicinity of the capital city, Port-au-Prince. Its effects on Haiti have been devastating (*Figure 1*). More than 150,000 bodies had been recovered by 25 January, and the official number of dead eventually reached 200,000. More than 250,000 people suffered often devastating injuries, and 1.2 million people were left homeless. The 2010 Haiti earthquake is considered one of the largest humanitarian catastrophes in history (Audefroy, 2011).



**Figure 1** Impacts on Port-au-Prince downtown infrastructures<sup>5</sup> (left) and Presidential building<sup>6</sup> (right).



**Figure 2** Impacts associated with the Hurricane Matthew<sup>7</sup>.

In October 4th 2016, the Caribbean island was hit by category 4 Hurricane Matthew, which was the most devastating disaster since the 2010 earthquake (*Figure 2*). Matthew affected about 1.125 million people in the country. The Haitian government assessed the death toll at

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<sup>5</sup> Source: [https://www.wired.com/2010/04/ff\\_haiti](https://www.wired.com/2010/04/ff_haiti)

<sup>6</sup> Source: [www.bahamaslocal.com/newsitem/1203](http://www.bahamaslocal.com/newsitem/1203)

<sup>7</sup> Sources: <http://www.scmp.com/news/world/united-states-canada/article/2026252/storm-lashes-florida-after-killing-more-800-haiti>; <http://www.daily-sun.com/post/173344/Haiti-hurricane-death-toll-double-to-800>

546, although other sources reported more than three times that figure. Over 500 schools were completely destroyed, and 3,400 public and private schools were damaged. In Haiti's Southern Peninsula, a third of all hospitals have been affected. Losses in agriculture, livestock, and fishing were estimated at US\$ 600 million (The World Bank, 2017).

Haiti will continue to be vulnerable to natural disasters. Located in the middle of the Caribbean Basin, 96% of the population of Haiti live in constant danger of two or more risks. Furthermore, Haiti has recently been identified as one of the most vulnerable countries to climate change. These observations have been confirmed by the alarming trend in successive disasters: 56 internationally recognised disasters, including 20 major disasters in the 20th century and 5 major disasters in the last 12 years alone (Government of the Republic of Haiti, 2010; The World Bank, 2017; Audefroy, 2011) (*Table 1*).

**Table 1** Summary of the last five disasters in Haiti. Sources: Government of the Republic of Haiti, 2010; The World Bank, 2017.

Event	Effect on GDP (GDP = US\$ 7,9 billion)	Individuals affected	Dead
2004 Hurricane Jeanne	7% of GDP	300,000	5,000
2007 Hurricanes Dean and Noel	2% of GDP	194,000	330
2008 Hurricanes Fay, Gustav, Hanna, and Ike	15% of GDP	1,000,000	800
2010 Earthquake	100% of GDP	2,000,000	200,000
2016 Hurricane Matthew	22% of GDP	1,125,000	546
<b>TOTAL</b>		<b>4,619,000</b>	<b>206,676</b>

### 2.3. SOCIAL CONTEXT

Prior to the earthquake, the basic human rights of many Haitians were not being realised: the right to work, safety and protection from exploitation, non-discrimination, health and education, due process, and gender equality (Government of the Republic of Haiti, 2010).

Most Haitians have no retirement provision, no social security, and no savings. Income distribution is particularly unequal in Haiti: the richest 1 percent owns the same wealth as 45 percent of the poorest population (United Nations Development Programme, 2013).

A provisional employment survey carried out by the Haitian Institute of Statistics and Informatics (IHSI) in 2007 shows a significant increase in poverty in the urban areas



(Government of the Republic of Haiti, 2010), where 58.6% of the population live (United Nations Development Programme, 2013). However, the greatest poverty levels are still in rural areas (Government of the Republic of Haiti, 2010).

The net enrolment rate in primary education has increased steadily from 47% in 1993 to 88% in 2011. However, the mean years of schooling is 3.9 and 6.6 for females and males, respectively. In contrast to primary education enrolment, the percentage of women and men older than 25 years old with at least some secondary education falls to 26% and 37%, respectively (United Nations Development Programme, 2013).

Work concerning gender equality was started two decades ago. Protocols were signed with the Ministries of Justice, Health, and Education to ensure that gender was taken into account. Women occupy more than 20 percent of government positions, but only 4.3 percent of seats in parliament (United Nations Development Programme, 2013). However, discriminatory clauses still exist in some laws and rules, and sexist stereotypes persist, as does violence against women. There has been a poor institutional response, and the budget for promoting women's rights is very inadequate. No sex-specific data has yet been collected. Nevertheless, international indices reflect the existence of a significant level of inequality. For example, Haiti is characterized by a Gender Inequality Index<sup>8</sup> (GII) of 0.593 (whereby a value of 1 is related to high discrimination).

In the aftermath of the Haiti earthquake, living conditions are growing visibly worse both for men and for women (*Figure 3*). Access to the basic services of water and sanitation are 65% and 34%, respectively, in urban areas. In the rural context, these values are much lower, at 48% and 19%, respectively (Joint Monitoring Programme, 2015).



**Figure 3** *Deterioration of living conditions among Haiti citizens<sup>9</sup>.*

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<sup>8</sup> Detailed information regarding index construction at <http://hdr.undp.org/en>

<sup>9</sup> Sources: <https://www.mprnews.org/story/2010/02/11/haitians-help-themselves>;  
<http://nicholaskrlev.com/2010/03/18/donate-miles-or-money-to-haiti/>

The death toll among young people in the earthquake was high – 75,000. Now, in the wake of the earthquake, 103,000 cases of children without any family protection have been reported. These children are at increased risk of violence and exploitation and have no access to any basic services, support systems, or advice. Young people have stopped attending school. The situation for young people in the camps is especially fragile. For most, relaxation, development, and entertainment are empty concepts. There have been an increased number of people with special needs (physically and mentally disabled). There is a poorer quality of support and assistance for people in difficult situations associated with emotional problems resulting from the loss of family and friends. The Ministry for Women's central office suffered heavy damage. Increased promiscuity and problems with sexual violence have increased. Women who are sole providers for a family, and other special needs groups (street children, orphans, old people, sick people, etc.) are now more vulnerable (Government of the Republic of Haiti, 2010).

## 2.4. ENVIRONMENTAL ASPECTS

Profound imbalances were present in both the natural and human environments prior to the earthquake. These were due to: i) acute poverty, ii) an economy which was largely subsistence-based, iii) a geological, geomorphological, and climatic context exposing the country to a broad spectrum of hazardous natural phenomena, and iv) a chronic inability of governance systems to ensure the effectiveness and viability of resource and land management, disaster risk management, and pollution control, whether in natural, rural, or urban environments (Government of the Republic of Haiti, 2010).

The erosion of watersheds, poor management of solid and liquid waste due to the installation of slums, and the absence of integrated management of the water resource have led to a quantitative and qualitative decrease in the water available (Government of the Republic of Haiti, 2010).

Haiti's climate is tropical with some variation depending on altitude. There are two rainy seasons, April—June and October—November. As an example, Port-au-Prince receives an average annual rainfall of 1,370 mm. Haiti is subject to periodic droughts and floods, made more severe by deforestation.

National forest cover, corresponding to the residue of natural forest land, had been estimated to be around 3% to 4% (Food and Agriculture Organization of United Nations, 2000; 2005). In contrast, a more recent research increases this value up to 30% (Churches et al., 2014). The proportion of woodland is the direct result of the high demand for domestic energy, 72% of which was met by wood fuel (Government of the Republic of Haiti, 2010).

Regarding solid waste and wastewater management, the situation was not better prior to earthquake (*Figure 4*). Solid waste was not appropriately managed; a common non-controlled incineration of piles of waste was the rule in practically all of the country, leading to constant air pollution. On the other hand, most of the water used in urban areas was transformed into wastewater and, in one way or another, returned to the natural environment without any treatment. Haiti does not have any form of modern sewer network or wastewater treatment systems (Government of the Republic of Haiti, 2010).



**Figure 4** *Environmental impacts associated to the solid waste and wastewater management<sup>10</sup>.*

Some of the earthquake impacts were related to the extensive destruction of buildings and equipment belonging to the Ministry of Environment (MDE) and several of its partners, and to the substantial loss of technical capabilities and institutional memory, in some cases up to and including the virtually total disappearance of an institution (e.g. the National Centre for Geo-Spatial Information). Furthermore, there is a risk of water pollution from waste and the debris from collapsed houses. The vulnerability of the population has increased due to the fact that some of the victims of the earthquake are now sheltering on river banks, near ravines, or close to the coast. With the increased price of wood fuel, timber resources are more sought-after than ever and subject to additional pressure. There is therefore a real risk of worsening the degradation of land and reducing the quantity and quality of environmental goods and services, such as water production, soil productivity, biological diversity, and flood and erosion protection. The structural problems regarding solid waste and wastewater management have been amplified in proportion to the consequences of the earthquake. There are piles of refuse lying in the streets, obstructing vehicle and pedestrian traffic. These block the drains, making towns highly vulnerable to flooding. The earthquake has significantly worsened sanitary conditions, especially in the refugee camps, where even minimum sanitary installations (such as pit latrines) are not available. In many places, pit latrines are not appropriate due to a lack of space and also because the pits and containers

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<sup>10</sup> Sources: <https://jordanmarieackerman.wordpress.com/category/southern-methodist-university/>;  
<http://www.hcdpinc.org/waste.php>

need constant emptying. Furthermore, the effects of the rainy seasons exacerbate these sanitary and environmental problems (Government of the Republic of Haiti, 2010).

## 2.5. ECONOMIC ISSUES

Haiti remains the poorest country in the Americas, and it is among the 20 poorest in the world, with a Gross Domestic Product (GDP) of US\$ 7.9 billion and a GDP per capita of US\$ 719 (International Monetary Fund, 2017). According to the latest Survey on Households' Living Conditions after the Earthquake in 2012 (ECVMAS, by its acronym in French), more than 6 million out of 10.6 million Haitians (56%) live under the national poverty line of US\$ 2.42 per day, and over 2.5 million (24%) live under the national extreme poverty line of US\$1.23 per day.

According to the Post-Disaster Needs Assessment (PDNA) of 2010, the agricultural sector's contribution (including animal husbandry, silviculture, and fishing) to the real GDP has fallen from more than 30% at the beginning of the 1990s, to 25.2% in 2007. Industry's contribution to the GDP (including construction) is about 25%, and commerce (including hotels and restaurants) contributes 27%. The agricultural sector is first in employment terms, with almost 50% of the working population, followed by tourism and transport (28% of the population) and industry (10.4% of jobs and commerce). Estimates show that 90% of all people working in industry and commerce are in the informal sector. Only 2% of working people are in the public sector.

A survey of Haiti's youth carried out before the earthquake (FAFO, 2009) showed that 35% of 15–24 year-olds were unemployed. Most of them, chiefly girls and young women, devoted themselves to unpaid domestic tasks (Government of the Republic of Haiti, 2010).

The earthquake caused job losses because places of work, equipment, stock, access to markets, and energy sources were destroyed. Employment was indirectly affected by market contraction, loss of finance, and the loss of qualified staff, and thus became less competitive. The main losses were in the service sector (education, health, transport, tourism). Women were particularly badly affected in the commercial sector (working from home, in the street, or at markets).

## 2.6. GOVERNANCE ASPECTS

As reflected in the PDNA Report (2010), governance-related issues suffered serious impacts. Prior to the earthquake, Haiti's public administration was already suffering from serious structural problems. Like the other national institutions, it did not have the trust of the population, who perceived it to be incapable of supplying essential services and to be affected by endemic corruption. The lack of technical skills and diligence and a lack of resources greatly limited the capacity to meet the population's demands for basic services. Following the earthquake, the public administration has sustained very high human and material losses. The destruction of office equipment, files, and computer data has affected several key Ministries that were in the affected buildings, constituting major damage for the sector.

The rule of law, justice, and security were in a difficult situation as well before the earthquake. The reforms implemented (particularly the laws of 2007) had had little impact; access to the public justice service remained very difficult. The system was not very effective, and the independence of the judiciary remained problematic. In terms of security, although the 2006 reform improved the situation, human and material resources remained highly insufficient. About 80% of the justice sector in Port-au-Prince was affected by the earthquake, with 49 justice-related buildings damaged and the archives largely destroyed. Judicial activity has been considerably reduced. The earthquake is going to lead to many civil law disputes, which will be made more difficult by the absence of land registry records and problems with birth, marriage, and death registrations.

## 2.7. HOUSING SECTOR

As explained in McWilliams & Griffin (2013):

“As a result of the 2010 earthquake, there has been an estimated 250,000 homes and 30,000 workplaces and shops either destroyed or badly damaged. Because of Haiti's use of poor construction techniques, and its general use of concrete, the 7.0-magnitude earthquake caused more than double the fatalities of any previously recorded event of that magnitude. Although the plight of Haiti in the aftermath of the earthquake has attracted funding and sympathy, less consideration has been made for the long-term support of constructing sustainable, seismic resistant buildings. Post-disaster evaluations have revealed that the majority of Haiti's destruction was simply caused by the poor quality of construction materials, which proved too weak to resist the lateral and horizontal forces generated by the earthquake (Audefroy, 2011) (*Figure 5*).





**Figure 5** *On the left: Heavy concrete slabs spanned clearings longer than three metres. On the right: Weight of the slabs caused buildings to collapse like a house of cards. Source: Audefroy, 2011.*

Engineers, architects, scientists, and others have already recognized that the process of construction is dysfunctional if no building codes are in place and there are economic incentives to cut corners. Despite the awareness that has been made about poor techniques, engineers and architects are currently still proposing systems that are destined to be hazards once the next disaster occurs due to their continued use of masonry and concrete. Not only is the use of concrete economically and environmentally unsustainable, but concrete is also the most vulnerable material when seismic activities hit the surface. Virtually all the buildings destroyed in the 2010 earthquake were poorly constructed, non-engineered, masonry and concrete buildings. In addition to the poorly-considered mixtures and the lack of reinforcement, the overall weight of the large mass of these buildings caused the majority of injury and death.

Because of the minimal resources, the Haitian constructions of recent buildings and of those that have collapsed in the 2010 earthquake were all compacted with poor-quality concrete mixes (Fierro, 2010). While mixing concrete, local labour and builders will use the poorest quality of sand and save the more valuable sand for the exterior stucco of the buildings. As a result, over 90% of all structures in Haiti cannot withstand the after effects of natural disasters (Audefroy, 2011).

Even years after the devastating earthquake, there is still little care for the seismic vulnerability and the longevity of future buildings. One could argue today that their international practices can produce sustainable concrete structures that deny the use of poor mixtures and low-quality labour. But what they are not taking account for is the quality of concrete, post-earthquake. The question then is how sustainable can concrete be after it has deconstructed in a natural disaster. The sustainability of concrete in Haiti seems almost impractical and irresponsible. The simple fact of knowing that concrete, reinforced or not, will not outlast any earthquake in the Caribbean, should be the first clue to

completely depleting it from all future design proposals. Both the local and international stakeholders of reconstruction in Haiti should reconsider sustainable structural systems that will indefinitely remain functional after a natural disaster hits.

The main problem with industrial, international materials is that they have to be imported into Haiti, causing designers to cut costs elsewhere in the project design. Reinforced concrete is a very reliable building system, but only if it is constructed properly. Concrete and masonry construction has historically been sub-standard in Haiti (McWilliams & Griffin, 2013). In order to rebuild safely with concrete in Haiti, there would need to be widespread training and quality control (Bhatty, 2010, cited by McWilliams & Griffin, 2013).

It has been proven that replacing traditional local materials with concrete and concrete blocks is economically unsustainable and ultimately making structures more vulnerable (Audefroy, 2011). As a result of replacing traditional materials, people are rebuilding the best they can, without applying any anti-seismic technical specifications.

After investigating alternative methods of design, all construction systems often demonstrated better resilience to earthquakes than any other buildings constructed with modern materials, specifically relating to masonry. If it can be begun to draw from these traditional practices and recognize that this knowledge needs to evolve and innovate, then essentially it can be finally have the potential to reconstruct Haiti.



**Figure 6** *On the left: A lack of maintenance weakened walls, contributing to their collapse. On the right: A wooden house with the traditional twin-sloped roof. Source: Audefroy, 2011.*

If local materials are the key concept to future sustainability, it is needed to be smart about how the material is utilized and truly understand what makes a seismic reinforced structure. Just like any industrial material, locally sourced materials can be seismically responsive and have a long lifespan if built correctly.

In Haiti, extensive amount of concrete rubble and construction debris have formed huge barriers to reconstruction (DesRoches et al., 2011). But according to science and research, there has become a successful and sustainable strategy for managing concrete debris and using it as a construction material that has ultimately been tested to have the same compressive strength as the concrete used in the United States. As of today, the substandard concrete that Haitian's make has a compressive strength of 8.9 MPa (N/mm<sup>2</sup>), which is less than half the minimum strength for any U.S. concrete (DesRoches et al., 2011). The goal was to reach the minimum requirement of 21 MPa (N/mm<sup>2</sup>) by using concrete debris. However, the concrete as a recycled aggregate can only work effectively if the mix of materials is consistent and easily measured. The idea of recycling concrete debris is a positive approach for future designers, as it can help remove the remaining debris. However, the re-use of rubble as aggregate for new construction is currently problematic in Haiti due to the need for precise measurements and testing”.

### 3. CLASS ACTIVITY

The proposed class activity aims to encourage a discussion regarding several aspects introduced previously. In this sense, we recommend to provide the students with that material in advance.

This activity is divided in two sections or blocks, with a total duration of three hours. For the methodology, we propose to work in small groups (of 3 to 4 students); further details are given in each block of the activity.

#### **Class activity: Block I**

In the first part of the class activity, programmed for one and a half hours, we propose to get deeper into several indices used to measure globally the level of human development, gender equality, and multi-dimensional poverty. For this, *Table 2* should be filled out. First, information related to the indices mentioned above should be found. Second, dimensions and indicators should be identified. Finally, the objective of this exercise is to detail direct and indirect impacts (positive and negative) related to an improvement of the identified indicators.

Filling out *Table 2* should take between 30 and 40 minutes. Afterwards, about 20 minutes should be dedicated for a general discussion. In addition to this, students will be required to answer whether or not they agree with the existing indices, and whether they would add any other indicator.



**Table 2** Proposed indices, as the basis for the discussion about potential direct and indirect impacts

INDEX	DIMENSIONS	INDICATORS (Units)	DIRECT IMPACTS	INDIRECT IMPACTS
Human Development Index (HDI)				
Gender Equality Index (GII)				
Multidimensional Poverty Index (MPI)				

**Class activity: Block II**

As detailed in the contextualization of this case study, and regarding constructing infrastructure specifically, so many losses occurred in numerous distinct aspects. Ideally, recovering the entire infrastructure at once would be the best scenario.

**Table 3** Proposed infrastructure to rank regarding considered priority.

INFRASTRUCTURE	PRIORITY RANKING
Buildings for special needs groups (street children, orphans, old people, etc.)	
Recreational buildings for youth	
Households	
Health infrastructure	
Institutional buildings (government, justice, etc.)	
Solid and liquid waste infrastructure	
Educational buildings (schools, universities, etc.)	
Business infrastructures (primary and secondary sector)	
Offices for women support	
Transport infrastructure	

Unfortunately, however, such a scenario would be quite difficult to achieve. In this sense, and according to the information provided, *Table 3* proposes a list of potential infrastructures to rebuild. With the specific situation in mind, the students should be asked to rank the priority of rebuilding the infrastructures in the presented list from higher (1) to lower (10). In

order to be more specific, attention should be directed to the urban context, where more people are concentrated.

Each group will have 30 minutes to define their priority rankings. The last 30 minutes will be used for the general debate. This discussion should be used to share groups' rankings. In this sense, we recommend that the teacher shares the students' answers, for instance on a blackboard or any similar item. Thus, the debate should be focused on both the similarities and differences among perspectives. The idea is to give the students the opportunity to defend the reasons behind their decisions.

### 3.1. SOLUTION AND EVALUATION CRITERIA

#### Class activity: Block I

This activity does not have a single, specific solution, as it is an open-answer question. We therefore list several impacts in detail to provide a brief guide for encouraging the general discussion.

INDEX	DIMENSIONS	INDICATORS (units)	DIRECT IMPACTS	INDIRECT IMPACTS
HDI	Health	Life expectancy (years)	- Life in its general concept	- Migration - Widespread urbanization - Raising the global old-age dependency ratio - Implications for retirement ages, health services, elder care, social protection, and family relationships
	Education	Expected years of schooling (years)	- Improving early childhood development - Enhancing capabilities	- Increasing opportunities while growing up (self-realisation)
		Mean years of schooling (years)	- Improving early childhood development - Enhancing capabilities	- Increasing opportunities while growing up (self-realisation)
	Standard of living	GNI per capita (US\$)	- Reducing poverty - Building purchasing power	- Decreasing sustainable consumption (higher demand)

INDEX	DIMENSIONS	INDICATORS (units)	DIRECT IMPACTS	INDIRECT IMPACTS
GII	Health	Maternal ratio (deaths per 100.000 live births)	<ul style="list-style-type: none"> <li>- Increasing life expectancy</li> <li>- Reducing size of mono-parental families</li> </ul>	<ul style="list-style-type: none"> <li>- Associated impacts to life expectancy</li> </ul>
		Adolescent birth rate (births per 1,000 women aged 15–19)	<ul style="list-style-type: none"> <li>- Reducing educational drop-out</li> </ul>	<ul style="list-style-type: none"> <li>- Reducing adolescent mortality</li> <li>- Decreasing economic problems</li> <li>- Controlling population size (to some extent)</li> </ul>
	Empowerment	Parliamentary representation (% seats)	<ul style="list-style-type: none"> <li>- Participation in decision-making</li> <li>- Increasing equity</li> </ul>	<ul style="list-style-type: none"> <li>- Evolving norms, values and legal frameworks</li> </ul>
		Attainment at secondary and higher education (%)	<ul style="list-style-type: none"> <li>- Enhancing capabilities</li> </ul>	<ul style="list-style-type: none"> <li>- Getting more choices</li> </ul>
	Labour market	Labour market participation (%)	<ul style="list-style-type: none"> <li>- Expanding women's freedoms</li> </ul>	<ul style="list-style-type: none"> <li>- Promoting economic growth</li> <li>- Reducing household poverty</li> </ul>
MPI	Education	School attainment (6 years schooling - Y/N)	<ul style="list-style-type: none"> <li>- Increasing opportunities when growing up</li> <li>- Enhancing capabilities</li> </ul>	<ul style="list-style-type: none"> <li>- Getting more choices</li> <li>- Self-realisation</li> </ul>
		School attendance (one school-age child not enrolled in school - Y/N)	<ul style="list-style-type: none"> <li>- Improving early childhood development</li> <li>- Enhancing capabilities</li> </ul>	<ul style="list-style-type: none"> <li>- Getting more choices</li> </ul>
	Health	Nutrition (malnutrition - Y/N)	<ul style="list-style-type: none"> <li>- Reducing the risk of death</li> <li>- Improving early childhood development (physically and mentally)</li> </ul>	<ul style="list-style-type: none"> <li>- Reducing health costs</li> <li>- Increasing global equality</li> </ul>
		Child mortality (under 5 - Y/N)	<ul style="list-style-type: none"> <li>- Increasing life expectancy</li> </ul>	<ul style="list-style-type: none"> <li>- Associated impacts to life expectancy</li> </ul>
	Living conditions	Electricity (Y/N)	<ul style="list-style-type: none"> <li>- Improving human development and well-being</li> </ul>	<ul style="list-style-type: none"> <li>- Increasing security</li> <li>- Increasing demand and risk of non-renewable resources consumption</li> </ul>
		Drinking water (Y/N)	<ul style="list-style-type: none"> <li>- Decreasing the risk of communicable diseases such as cholera and diarrhoea</li> </ul>	<ul style="list-style-type: none"> <li>- Improving human development and well-being</li> <li>- Reducing health costs</li> </ul>
		Sanitation (Y/N)	<ul style="list-style-type: none"> <li>- Decreasing the risk of diseases</li> <li>- Improving common environment</li> </ul>	<ul style="list-style-type: none"> <li>- Improving human development and well-being</li> <li>- Improving water quality, thus water ecosystems</li> <li>- Reducing health costs</li> </ul>

INDEX	DIMENSIONS	INDICATORS (units)	DIRECT IMPACTS	INDIRECT IMPACTS
MPI	Living conditions	Cooking fuel (Y/N)	- Decreasing lung-related diseases	- Reducing health costs - Reducing non-renewable resources
		Household conditions (Y/N)	- Improving human well-being	- Enhancing capabilities
		Assets (Y/N)	- Improving communication and mobility	- Lifting up the economy

Please keep in mind that, due to the open nature of these questions, the ideas the students have about which new indicators to incorporate does not have to agree with the existing indices.

### **Class activity: Block II**

Similar to the last part of the Block I, no specific answers are provided for Block II. As mentioned above, the objective of Block II is to encourage the students to reflect, discuss, and share their different opinions and perspectives. One approach to organizing the debate could be to focus on the top and bottom 3 or 4 infrastructures selected, for instance.

### **Evaluation criteria**

In order to provide an objective and transparent evaluation system for students, we propose that a rubric is used (see *Annex III*). In this sense, the rubric shows: i) the knowledge that students are expected to acquire, and ii) the criteria used to evaluate the content of the answers associated with the proposed activities.

The way to apply this rubric starts by providing it to the students, in order to inform them how they will be evaluated. Therefore, some guidance should be given to them to allow them to focus on the specific goals (in terms of answers).

To facilitate evaluation, each group should submit (or give in paper format) the answers to the professor at the end of the class. These answers will be evaluated based on the rubric criteria. However, the teacher is free to choose an alternative evaluation method if she/he considers it to be more appropriate.

#### 4. HOMEWORK ACTIVITY

As in previous activity, this activity is clearly defined as two blocks. We recommend that both exercises are done in small groups (i.e. 3 or 4 students), but this can be left to the teacher's discretion. We estimate that the total activity will require 10 hours of work.

##### Homework activity: Block I

This first part aims to deal with the more technical aspects of designing concrete mix proportions. First, a mix proportion of conventional concrete employing raw aggregates should be determined. Second, a mix proportion of recycled aggregate concrete should be defined. In this case, the coarse raw aggregates, which were used for designing the mix proportion of conventional concrete in the first step, will be replaced by coarse recycled aggregate. In both cases, Haiti's context should be taken into consideration (i.e. environmental exposure class conditions). In addition, the methodology of Bolomey will be applied to calculate the mass of the materials to employ in 5,000 litres of concrete. In this sense, there are some starting data to take into account.

##### Raw aggregates concrete

- As there is no specific Normative in Haiti, the one that applies in Spain for the calculation of concrete structures (EHE-08<sup>11</sup>) will be used.
- The selection of the maximum water /cement ratio, as well as the minimum content of cement, should be done according to *Table 4*. Concrete type should be taken into account.

**Table 4** Maximum water/cement (w/c) ratio and minimum cement content.

MIX PROP.	CONCRETE TYPE	EXPOSURE CLASS												
		I	IIa	IIb	IIIa	IIIb	IIIc	IV	Qa	Qb	Qc	H	F	E
Maximum ratio w/c	Mass	0.65	---	---	---	---	---	---	0.50	0.50	0.45	0.55	0.50	0.50
	Reinforced	0.65	0.60	0.55	0.50	0.50	0.45	0.50	0.50	0.50	0.45	0.55	0.50	0.50
	Prestressed	0.60	0.60	0.55	0.50	0.45	0.45	0.45	0.50	0.45	0.45	0.55	0.50	0.50

<sup>11</sup> [https://www.fomento.gob.es/MFOM/LANG\\_CASTELLANO/ORGANOS\\_COLEGIADOS/MASORGANOS/CPH/instrucciones/EHE08INGLES](https://www.fomento.gob.es/MFOM/LANG_CASTELLANO/ORGANOS_COLEGIADOS/MASORGANOS/CPH/instrucciones/EHE08INGLES). Consult this link for detailed information related to EHE-08.

MIX PROP.	CONCRETE TYPE	EXPOSURE CLASS												
		I	IIa	IIb	IIIa	IIIb	IIIc	IV	Qa	Qb	Qc	H	F	E
Minimum content of cement (kg/m <sup>3</sup> )	Mass	200	---	---	---	---	---	---	275	300	325	275	300	275
	Reinforced	250	275	300	300	325	350	325	325	350	350	300	325	300
	Prestressed	275	300	300	300	325	350	325	325	350	350	300	325	300

- The grading distribution of aggregates specified in *Table 5* will be used in this activity. Here, the percentage of the aggregates that passes through the specific sieve is given.

**Table 5** Grading distribution of different fractions of raw aggregates used for conventional concrete production (% of passing through the sieves).

SIEVE OPENING (mm)	GRAVEL 1 - 10/20 - (%)	GRAVEL 2 - 5/10 - (%)	SAND - 0/5 - (%)
20	100	100	100
10	2	90	100
5	0	7	100
2.5	0	0	68
1.25	0	0	42
0.63	0	0	27
0.32	0	0	18
0.16	0	0	8
0.075	0	0	7

- As a guide, the density of 3.1 kg/dm<sup>3</sup> can be applied for the cement. The density of 2.6 kg/dm<sup>3</sup> can be employed in all the raw aggregates. Sand humidity of about 1% must be considered. The percentage of air will not be taken into account. The coefficient “a” integrated in the Bolomey expression should be chosen from *Table 6*.

**Table 6** Values for a coefficient of Bolomey.

AGGREGATE TYPE	CONSISTENCY	VALUES OF a
River	Dry-plastic	10
	Soft	11
	Fluid	12
Crushed	Dry-plastic	12
	Soft	13
	Fluid	14

- Once the concrete is produced, its compressive strength should be validated according to *Table 6*, in accordance with concrete type and the environmental exposure class. The obtained compressive strength should be 8 MPa higher than that described in *Table 7* in order to assure that 95% of the test specimens achieve the compressive strength.

**Table 7** Minimum strength recommended according to exposure classes

DOSAGE PARAMETER	CONCRETE TYPE	EXPOSURE CLASS												
		I	IIa	IIb	IIIa	IIIb	IIIc	IV	Qa	Qb	Qc	H	F	E
Minimum strength (N/mm <sup>2</sup> )	Mass	20	---	---	---	---	---	---	30	30	35	30	30	30
	Reinforced	25	25	30	30	30	35	30	30	30	35	30	30	30
	Prestressed	25	25	30	30	35	35	35	30	35	35	30	30	30

### Recycled aggregate concrete

In order to produce recycled aggregate concrete (RAC), the coarse raw aggregates (Gravel 1 and Gravel 2) will be replaced by coarse recycled aggregates (RA).

The following properties of recycled aggregates should take into account:

- Grading distribution of RA should be similar to that of raw aggregates;
- RA has a higher water absorption capacity than that of raw aggregates. RAs with the highest water absorption capacities have a lower quality. According to EHE standard

for structural concretes, the water absorption capacity of RA should be lower than 7%. For plain concrete and low-medium strength concrete, the replacement ratio of raw aggregates could be high, achieving up to 100% (depending on the application). However, reinforced recycled concretes exposed to aggressive environment should be produced employing RA with a water absorption capacity lower than 5% with the maximum replacement (in volume) of 50%;

- RAC production will be done with a replacement of 50% of RA;
- RA1, which will be used as a substitute for Gravel 1, has a density of  $2.2 \text{ kg/dm}^3$  and a water absorption capacity of 4.8%;
- RA2 has a density of  $2.12 \text{ kg/dm}^3$  and an absorption capacity of 5.4%;
- RA1 and RA2 will be employed with the humidity values of 3.8% and 4.3%, respectively;
- The water absorption capacity of Gravel 1, Gravel 2, and sand is 0.4%, 0.6%, and 1%, respectively;
- The same effective water/cement ratio will be used in both conventional and recycled concrete. In order to determine the effective water/cement ratio, the effective absorption capacity of all aggregates will be considered (absorption capacity of material submerging in water for 30 minutes). The effective absorption capacity of Gravel 1, Gravel 2, and sand are 20%, 20% and 70% of their water absorption capacity. The effective absorption capacity of both RAs (RA1 and RA2) is 80% of their absorption capacity.

As a last step, the main differences among the results regarding the use of recycled and raw aggregates should be discussed.

### Homework activity: Block II

In this second block, the students will be transferred to the context of Haiti. Specifically, they will be asked to design some guidelines for training and quality control. In this sense, two key aspects should be taken into consideration:

- The approach of using recycled aggregates rather than raw aggregates;
- The transfer of knowledge.



#### 4.1. SOLUTION AND EVALUATION CRITERIA

##### Homework activity: Block I

First, a summary of the starting data is introduced. Note that the first calculation is for 1 m<sup>3</sup> of concrete.

PARAMETER	DATA	UNITS
Minimum strength	30	N/mm <sup>2</sup>
Exposure	IIIa	---
Concrete type	Prestressed	---
Maximum ratio w/c	0.5	dimensionless
Minimum cement content	300	kg/m <sup>3</sup>
Consistency	Fluid	---
Aggregate type	Crushed	---
Coefficient a	14	dimensionless
$\rho_{\text{cement}}$	3.1	kg/dm <sup>3</sup>
$\rho_{\text{aggregates}}$	2.6	kg/dm <sup>3</sup>
Humidity <sub>sand</sub>	1	%

Next, the volume of water is calculated considering the minimum cement content and the ratio of water and cement:

$$V_{\text{water}} = 300 \times 0.5 = 150 \text{ kg (or litres)}$$

These 150 litres of water represent the maximum water (total water) that is allowed to be used for this concrete production.

The volume of cement required is:

$$V_{\text{cement}} = \frac{300 \text{ kg}}{3.1 \text{ kg/dm}^3} = 96.77 \text{ dm}^3 = 96.77 \text{ l}$$

According to the Bolomey methodology for fresh concrete as well as “by trial” procedures, the volume of cement and aggregates can be considered as a whole. Thus, it is possible to write:

$$1,025 = V_{H_2O} + V_{\text{cement+aggregates}}$$

Considering the volume water, we obtain:

$$V_{\text{cement+aggregates}} = 1,025 - 150 = 875 \text{ l}$$

It is now possible to calculate the percentage of cement using the previous volume. This value will be named as  $t_0$ :

$$t_0 = \frac{96.77}{875} = 0.1105 \text{ (or 11.05\%)}$$

Bolomey’s methodology states that the dosage of the aggregates is determined by a reference curve, which represents a continuous grading distribution and maximum compactness between the aggregates, achieving the maximum density. This standard curve is represented by the following equation:

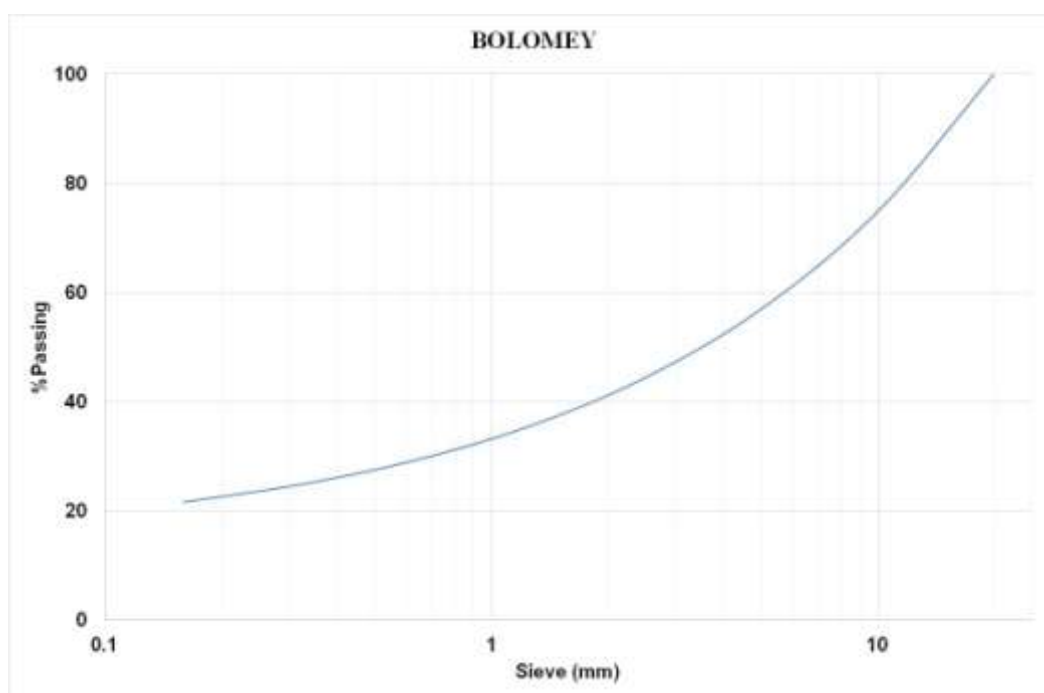
$$y = a + (100 - a) \times \sqrt{\frac{d}{D}}$$

When using the “by trial” procedure, the term of the equation  $d/D_{\max}$  is defined as  $d/20$  (note  $D_{\max} = 20$  is the smallest sieve that allows more than 90% of the fraction to pass through). In this way, all the sieves are taken into account ( $d$ ). As a result, the following results are obtained:

Sieve opening	Gravel 1 ( $t_3$ )	Gravel 2 ( $t_2$ )	Sand ( $t_1$ )	Cement ( $t_0$ )	Bolomey
20	100	100	100	11.05	100.00
10	2	90	100	11.05	74.81
5	0	7	100	11.05	57.00
2.5	0	0	68	11.05	44.41
1.25	0	0	42	11.05	35.50
0.63	0	0	27	11.05	29.26

Sieve opening	Gravel 1 ( $t_3$ )	Gravel 2 ( $t_2$ )	Sand ( $t_1$ )	Cement ( $t_0$ )	Bolomey
0.32	0	0	18	11.05	24.88
0.16	0	0	8	11.05	21.69

Thus, the theoretical curve of Bolomey can be represented as follows:



In order to obtain the real curve, those  $d/D$  for which 90% or more of the aggregates pass through are considered. Thus, a system of three equations can be formulated:

- Sieve 20:  $t_0 + t_1 + t_2 + t_3 = 100$
- Sieve 10:  $t_0 + t_1 + t_2 = 74.81$
- Sieve 5:  $t_0 + t_1 = 57$

From these equations, the following values are obtained (in percentage):

- $t_1 = 45.95 \% = 0.4595$
- $t_2 = 17.81 \% = 0.1781$

- $t_3 = 25.19 \% = 0.2519$

With these values, the real curve can be visualized by operating in the following form:

$$\text{Sieve 20} = 100t_3 + 100t_2 + 100t_1 + 100t_0$$

$$\text{Sieve 10} = 100t_2 + 100t_1 + 100t_0$$

$$\text{Sieve 5} = 100t_1 + 100t_0$$

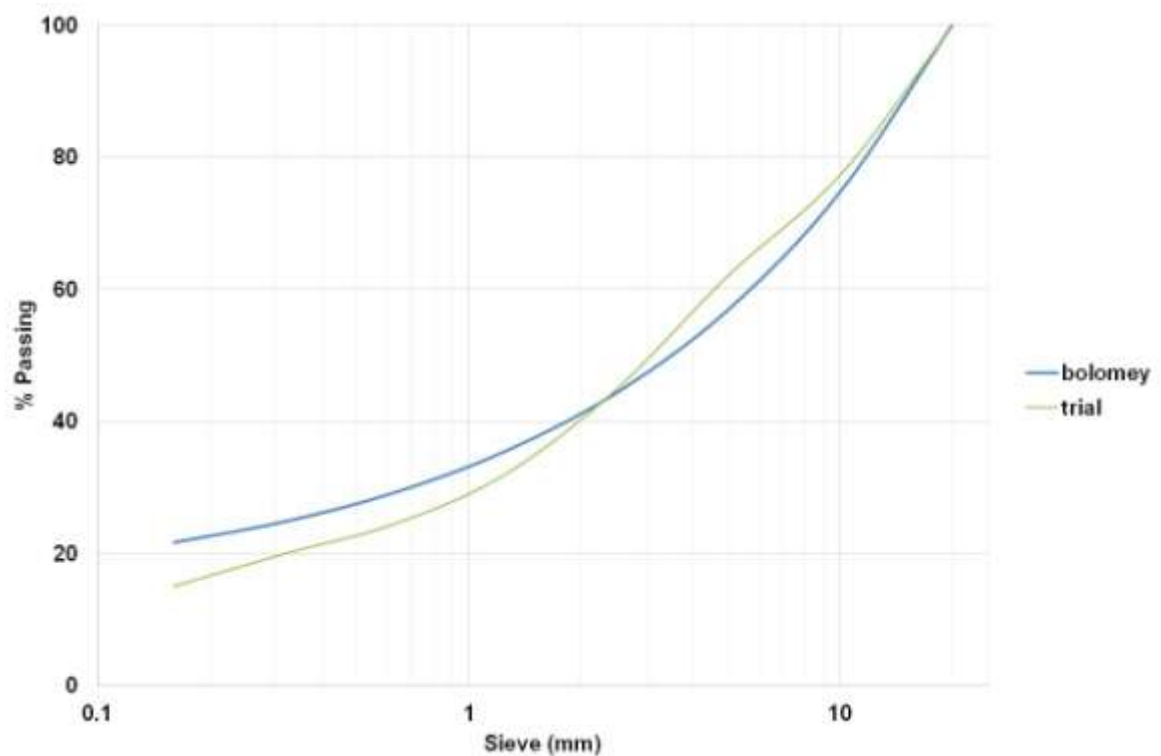
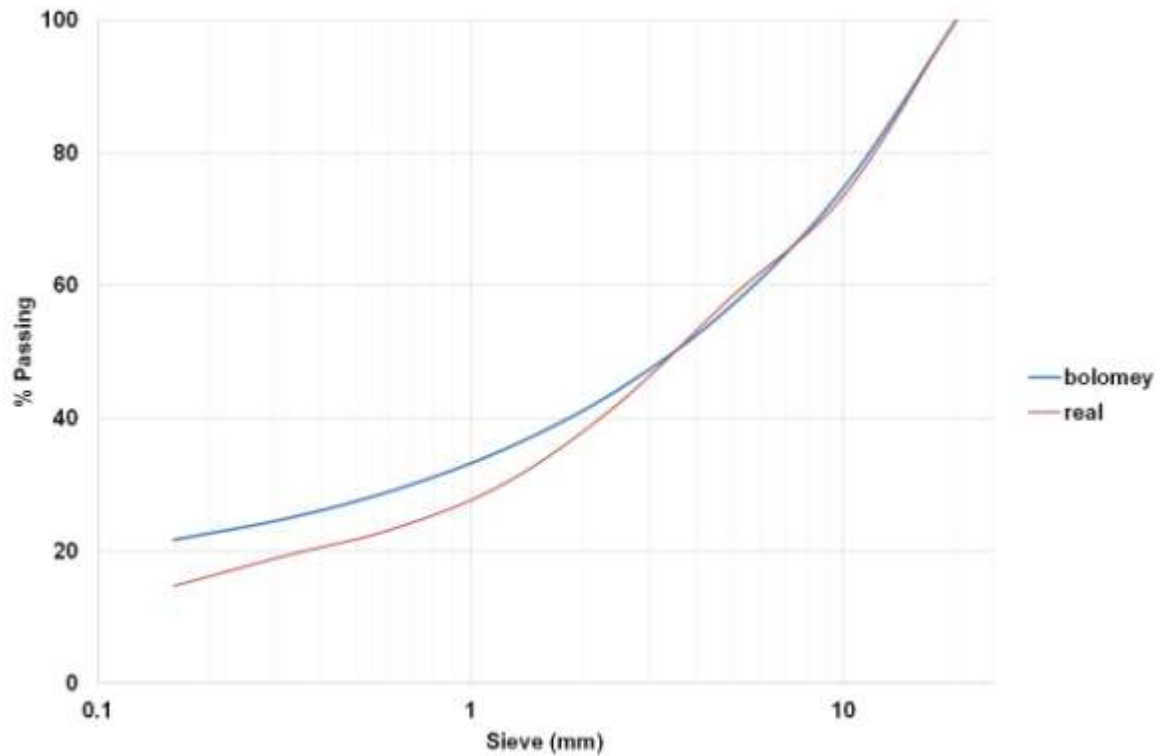
...

$$\text{Sieve 0.16} = 100t_1 + 100t_0$$

Sieve opening	Gravel 1 ( $t_3$ )	Gravel 2 ( $t_2$ )	Sand ( $t_1$ )	Cement ( $t_0$ )	Bolomey	Real
20	100	100	100	11.05	100	100
10	2	90	100	11.05	74.81	73.03
5	0	7	100	11.05	57	57
2.5	0	0	68	11.05	44.41	42.30
1.25	0	0	42	11.05	35.50	30.35
0.63	0	0	27	11.05	29.26	23.46
0.32	0	0	18	11.05	24.88	19.32
0.16	0	0	8	11.05	21.69	14.73

From the graph below, it can be seen that the curves are different. Those areas where the real curve is under the theoretical one means that less aggregates pass through the sieves, while those areas over the theoretical curve mean the opposite. In this sense, what should be looked for is a similar area over and under that theoretical curve. This would mean an appropriate compaction of the mixture. From the graph, it is possible to see that those aggregates associated to the sieves  $\leq 5$  are under the theoretical curve. By applying the “by trial” procedure, different attempts are done in order to achieve the objective mentioned previously. In so doing, as an example, the percentage of sand can be increased, while reducing gravel 1. In following graph, the percentage of sand was increased, and the

percentage of gravel 1 decreased, by 4%; gravel 2 was constant. Thus, the result obtained with the trial carried seems to be appropriate.



Then, the percentages of the different aggregates and the cement can be detailed as follows:

- $t_0 = 11.05\%$
- $t_1 = 49.95\%$
- $t_2 = 17.81\%$
- $t_3 = 21.19\%$

Consequently, the different volumes and masses are:

$$t_1 = V_{\text{sand}} = 875 \text{ l} \times 0.4995 = 437.1 \text{ l}$$

$$m_{\text{sand}} = 437.1 \text{ l} \times 2.6 \frac{\text{kg}}{\text{l}} = 1,136.5 \text{ kg}$$

$$t_2 = V_{\text{gravel 2}} = 875 \text{ l} \times 0.1781 = 155.8 \text{ l}$$

$$m_{\text{gravel 2}} = 155.8 \text{ l} \times 2.6 \frac{\text{kg}}{\text{l}} = 405.1 \text{ kg}$$

$$t_3 = V_{\text{gravel 1}} = 875 \text{ l} \times 0.2119 = 185.4 \text{ l}$$

$$m_{\text{gravel 1}} = 185.4 \text{ l} \times 2.6 \frac{\text{kg}}{\text{l}} = 482.0 \text{ kg}$$

However, it should also be taken into account that sand is wet, with 1% humidity. The previous calculations were related to dry aggregates. Thus, the real amount of sand can be obtained as follows:

$$m_{\text{sand}} = 1,136.5 \text{ kg} \times \frac{100}{99} = 1,147.9 \text{ kg}$$

The weight difference between wet and dry aggregates is 11.5 kg, which is water. As it was defined previously, the maximum water that is allowed to be used in this concrete is 150 litres; consequently, the water to be added to mixing machine will be  $150 - 11.5 = 138.5$  litres.

Finally, the following table presents both the dosage to elaborate  $1 \text{ m}^3$  and 5000 litres, which was the objective of the exercise.

Material	Mix proportion for 1 m <sup>3</sup>	Mix proportion for 5 m <sup>3</sup>
Cement	300 kg	1,500 kg
Water	138.5 kg	692.5 kg
Gravel 1	482 kg	2,410 kg
Gravel 2	405.1 kg	2,025.5 kg
Sand	1147.9 kg	5,739.5 kg

This is the final mix proportion for conventional concrete, using only raw aggregates.

#### Design of recycled aggregate concrete

The mix proportion of recycled aggregate concrete (RAC) has to be designed employing the replacement (by volume) of 50% of raw aggregates by recycled aggregates, as described previously.

The total water employed in RAC will be determined by considering that the total water employed in conventional concrete is 150 litres, and that both concretes have the same effective water/cement ratio.

The following table shows the mix proportion of conventional concrete:

Material	Mix proportion for 1 m <sup>3</sup>
Cement	300 kg
Water	138.5 kg
Gravel 1	482 kg
Gravel 2	405.1 kg
Sand	1,147.9 kg

Replacing 50% of coarse raw aggregates (in volume) by recycled aggregates, the values detailed below are obtained:

#### Gravel 1

Volume =  $482 / 2.6 = 185.4$  litres, 50% of volume: 92.7 litres

$m_{\text{gravel1}} = 92.7 \times 2.6 = 241.02$  kg

$$m_{RA1} = 92.7 \times 2.2 = 203.94 \text{ kg (dry mass)}$$

$$m_{RA1\text{-wet}} = 203.94 \times (100 / 96.2) = 211.99 \text{ kg}$$

### Gravel 2

$$\text{Volume} = 405.1 / 2.6 = 155.8 \text{ litres, 50\% of volume: } 77.9 \text{ litres}$$

$$m_{\text{gravel}2} = 77.9 \times 2.6 = 202.54 \text{ kg}$$

$$m_{RA2} = 77.9 \times 2.12 = 165.15 \text{ kg}$$

$$m_{RA2\text{-wet}} = 165.15 \times (100 / 95.7) = 172.57 \text{ kg}$$

### Sand

$$m_{\text{sand}} = 1,147.9 \text{ kg}$$

### Cement

$$m_{\text{cement}} = 300 \text{ kg}$$

### Water

A total water amount of 150 kg was used for the conventional concrete production. Sand has a humidity of 1% (11.5 kg of water) and consequently, 138.5 kg of water is added to concrete production. Due to the effective absorption capacity of raw aggregates, the free water (which reacts with cement and describes the effective water/cement ratio) is calculated by the water added minus the effective absorption capacity of the aggregates.

The effective absorption capacity of Gravel 1 and Gravel 2 are 20% of its absorption capacity. Gravel 1 and Gravel 2 water absorption capacity are 0.4% and 0.6%, respectively. Thus, the effective absorption capacity of Gravel 1 and Gravel 2 are 0.08% and 0.12%. For sand, the effective absorption capacity is 70% of its absorption capacity. Consequently, effective absorption capacity of sand is 0.7%. However, sand already has 1% humidity, so the absorption capacity can be considered as 0 (e.g., its absorption capacity of 1% is filled).

The water mixed for concrete production was 138.5 kg ( $m_{\text{water}}$ ). Due to effective absorbed water, the free water is:

$$m_{\text{free water}} = 138.5 - (482 \times 0.08 / 100) - (405.1 \times 0.12 / 100) = 137.63 \text{ kg (free water in conventional concrete and recycled aggregate concrete)}$$

Thus, 137.63 kg of water is the constant value to maintain in both conventional and recycled concretes.

Next, the water that is required to add for recycled aggregate concrete production will be the free water (137.63 kg) plus the water effectively absorbed for the aggregates.



RA1 has a humidity of 3.8% and an absorption capacity of 4.8%. So, the real absorption capacity at production time is 1%. The effective absorption capacity is 80% of its absorption capacity. Thus, the effective absorption capacity is 0.8%.

Following the same procedure, RA2 has a humidity of 4.3% and an absorption capacity of 5.4%. The effective absorption capacity is thus  $1.1\% \times 80\%$ , which is equal to 0.88%.

The total water required to be added is:

$$m_{\text{total water}} = 137.63 + (241.02 \times 0.08/100) + (202.54 \times 0.12/100) + (211.99 \times 0.8/100) + (172.57 \times 0.88/100) = 141.28 \text{ litres}$$

Finally, the mix proportion of RAC production for 1 and 5 m<sup>3</sup> is:

Material	Mix proportion for 1 m <sup>3</sup>	Mix proportion for 5 m <sup>3</sup>
Cement	300 kg	1500 kg
Water	141.28 kg	706.4 kg
Gravel 1	241.02 kg	1,205.1 kg
RA1	211.99 kg	1,059.95 kg
Gravel 2	202.54 kg	1,012.7 kg
RA2	172.57 kg	862.85 kg
Sand	1,147.9 kg	5,739.5

Comparing both conventional and recycled aggregate concrete reveals that the difference in water required is low (14 kg per 5 m<sup>3</sup>).

Material	Conventional mix for 5 m <sup>3</sup>	Recycled aggregates mix for 5 m <sup>3</sup>
Cement	1,500 kg	1,500 kg
Water	692.5 kg	706.4 kg
Gravel 1	2,410 kg	1,205.1 kg
RA1	---	1,059.95 kg
Gravel 2	2,025.5 kg	1,012.7 kg

Material	Conventional mix for 5 m <sup>3</sup>	Recycled aggregates mix for 5 m <sup>3</sup>
RA2	---	862.85 kg
Sand	5,739.5 kg	5,739.5 kg

However, these results refer to the case of RA with content water (humidity). Even if humid RA is recommended for concrete elaboration, it is interesting to determine the total amount of water employed for RAC production. In this sense, the total amount of water in RAC would be the one resulting from the water added plus the water present in form of humidity in sand, RA1, and RA2.

$$M_{\text{required}} = 141.28 + (1,147.9 - 1,136.5) + (211.99 - 203.94) + (172.57 - 165.15) = 168.15 \text{ litres}$$

Whereas RAC requires a total amount of water of 168.15 litres, conventional concrete requires 150 litres when using dried aggregates. This is due to the high water absorption capacity of RA.

On the other hand, and due to absorption mentioned previously, it is relevant to mention that the compressive strength of RAC will be lower than that of conventional concrete. Consequently, it is recommended that a lower water/cement maximum ratio (4–10%), and a higher proportion of cement (5–10%), is used than in conventional concrete. Thus, the same compression strength, as well as durability properties, will be achieved (at 28 days). This potential solution must be verified by checking the correspondence in volume among the materials employed.

### Homework activity: Block II

As for the class activity, this activity does not have a unique solution. This part of the activity is an open-answer, and students are requested to think of the solution they consider most appropriate. Although providing more details is a task for the students, several aspects that could be taken into consideration are presented below:

#### The approach of using recycled aggregates rather than raw aggregates

Using recycled aggregates seems to be an appropriate approach considering the existing amount in Haiti. Nevertheless, an important aspect to take into account is the quality of these aggregates. If the quality is not appropriate, the resulting RAC will not be either. In this sense, aggregates containing sulphates or chlorides (aggregates from sea) should be avoided. While chloride content should be taken into account when reinforced concrete is

produced, it is less important in plain concrete (e.g. concrete blocks). Thus, a quality control is remarkably necessary.

Regarding this quality control, the participation of both public and private sectors should be encouraged. The aim is to ensure that the merchandising of these materials satisfy the required characteristics. Documentation, quality certificates, and detailed information, among others, are mechanisms to provide a transparent market.

Quality control is also about controlling the characteristic of the water used. This aspect is relevant for both conventional and RA concrete elaboration. This last one requires higher quantities of water, which is a factor to consider as far as its availability in any geographic area given. Water scarcity might be an aspect to take into account when deciding which concrete to elaborate.

Another element to evaluate is the cost associated to material transportation. There is no doubt that employing RA can reduce costs. On the other hand, the use of local materials or, if not possible, of neighbouring countries (i.e. Dominican Republic, Cuba, Jamaica, etc.) should be encouraged. In any case, quality controls should be demanded from the providers. In addition, using a local market has less negative environmental impacts.

### *The transfer of knowledge*

One of the most important aspects to take into account is to understand the current practises of the professionals and non-professionals of the country. Transferring knowledge is not about imposing ideas but rather understanding the context, sharing point of views, and converging in consensus solutions.

As described in the contextualization of this case study, traditional construction systems have been found to often demonstrate better resilience to earthquakes than any other buildings constructed with modern materials, and specifically those relating to masonry. Thus, identifying potential inappropriate practices can be a starting point. Incorporating traditional practices and recognizing that this knowledge needs to evolve and innovate definitely could build dialogue and a holistic path.

A first characteristic of this path could be the establishment of a construction normative, as there is currently a lack of any building code in the country. Considering that an important proportion of the population speaks French and English, using normatives from countries that speak these languages would provide a solid guide. However, the effort to translate it to the official language should also be done.

Knowledge transfer should be applied by facilitating spaces where professionals and non-professionals will be trained. Another important aspect is to encourage women to participate in this regard. Collaboration with local stakeholders and institutions, public and private sectors, superior education centres, NGOs, etc. would be an added value. Training should be done from the perspective of educating future educators. One approach could be the elaboration of different training programs focused on the different phases involving the construction: design, execution, maintenance, and control.

One of the aspects that should be transmitted in the easiest and most pedagogic way possible is how to carry out an appropriate mixing of materials when elaborating both conventional and RA concrete. Availability of working materials should be taken into consideration when designing the strategy of using these procedures. Calculating the absorption capacity of aggregates, or reinforcing structures through different solutions, should be aspects that are paid special attention to as well. In any case, the temporal factor should be considered when designing and implementing any solution. The overall objective is to avoid a catastrophe similar to the 2010 earthquake.

### **Evaluation criteria**

In order to evaluate this activity, a report will be requested from each group, in which the entire activity should be solved.

For the specific assessment of the report, we recommend using the rubric presented previously (see Annex III), and specifically, the technical aspects identified within the rubric. However, and depending on the responses of the students, aspects other than those included in the rubric should be considered. Thus, the rubric represents a possible instrument to facilitate the evaluation of the proposed activities as a whole. As mentioned above, the professor is free to choose an alternative method.

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# Widening Horizons to the Design of Pre-stressed Concrete Slab: A Case Study of Barcelona

David Requejo Castro and Eva Oller



PHOTO: Ronda de Dalt, Barcelona. ©ESTEYCO.





# CASE STUDIES **Widening Horizons to the Design of Pre-stressed Concrete Slab: A Case Study of Barcelona**

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# 4 WIDENING HORIZONS TO THE DESIGN OF A PRE- STRESSED CONCRETE SLAB: A CASE STUDY IN BARCELONA

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## 1. INTRODUCTION

Only one century ago, 20% of the world's population resided in urban areas. In lower income countries, this proportion was just 5%. Today, approximately half of humanity lives in cities (3.5 billion people).

At the United Nations Conference on Human Settlements in 1976 (Vancouver, Canada), the international community was called to commit to human settlement policies in order to alleviate the worst conditions of “uncontrolled urbanization” within a framework of social justice. Two decades later, within the definition of the Millennium Development Goals (MDGs), world leaders shaped a broad vision to fight poverty in its many dimensions for the next 15 years. Among these goals, and regarding urbanization issues, a specific target was included to achieve, by 2020, a significant improvement in the lives of at least 100 million slum dwellers. The result during the MDG period was a reduction of the proportion of urban population living in slums in the low-income regions from approximately 39.4% to 29.7%. Nevertheless, key current and new urban challenges have emerged over the years. In 2015, countries adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs). In this context, a more ambitious spectrum was defined — to “make cities inclusive, safe, resilient and sustainable” (Goal 11).

Undoubtedly, engineers, as well as other practitioners, play a key role in achieving more sustainable cities. Further, simply applying only technical solutions is unrealistic. In this sense, a shift towards a wider perspective is needed, and professionals are being called on to extend their role to include ensuring that the real needs of all present end users are met, as well as recognizing impacts on both the natural environment and future generations.

In this case study, students are invited to apply their technical skills while, at the same time, are encouraged to discuss different aspects that integrate a wider perspective into decision-making. To do this, an introduction is provided for the international context addressing the human settlements as well as for the concept of sustainable development. In addition to this, basic knowledge will be provided regarding index construction for supporting decision-making. Finally, a specific context and problem will be introduced in order to set up the starting point for the proposed activities development.

### 1.1. DISCIPLINES COVERED

The main discipline covered in this case study refers to pre-stressed concrete structures. Nevertheless, several concepts, including teaching methodology, can be the base for disciplines related to reinforced concrete structures or to steel structures.

In parallel, teamwork is promoted, as the proposed activities are to be carried out in small groups, which ultimately should stimulate both group enrichment discussions and a general debate in the classroom.

## 1.2. LEARNING OUTCOMES

It is expected that, as a result of this case study, students will be able to:

- Understand current situation regarding human settlements and the importance of sustainable approaches;
- Deal with the definition of a solution to a real project, trying to understand the problem in hand from its conception;
- Learn to think as an engineer, by solving problems with multiple solutions and trying to choose the optimal one;
- Wide their perspectives when dealing with any project, integrating into their decisions several aspects rather than only the technical ones;
- Define the structural solution (geometry, active and passive internal reinforcement) by accomplishing the conditions given by the existing concrete codes (in this case, the Spanish Concrete Code EHE-08 and Eurocode-2).

## 1.3. ACTIVITIES

In this case study, two activities are requested from the students. The first will be a reflection about the complexity of human development from the perspective of civil engineering. This should encourage not only an enriching debate but also a discussion that reaches beyond the technical and economic aspects that are usually considered during the design of a project.

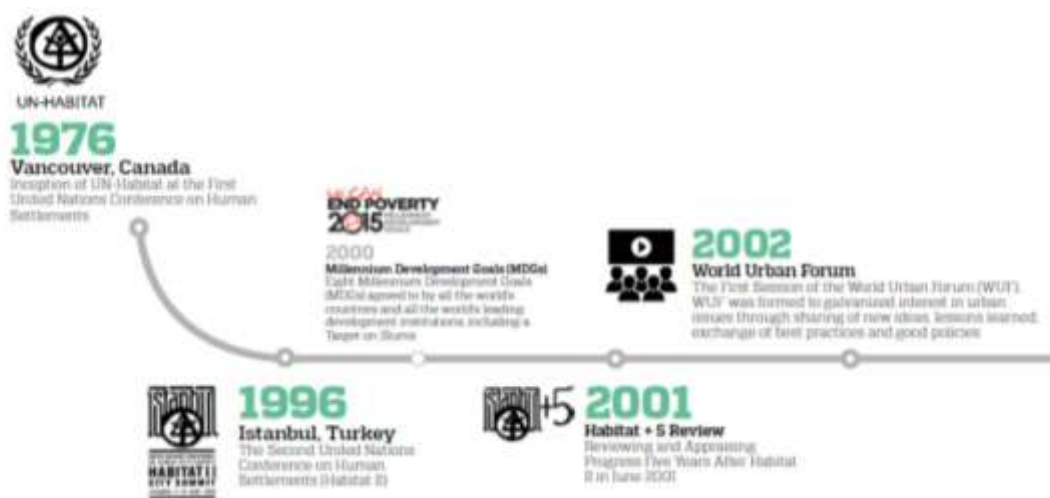
The second activity, designed to be solved during an academic semester, aims to work on the technical solution associated with the presented problem. Furthermore, the solutions proposed are expected to be justified and linked to the deontological code of engineers.

## 2. DESCRIPTION OF THE CONTEXT

In this section, we present an introduction of the international context addressing human settlements and a global overview of the urbanization, to provide the students with a general perspective of this global issue. Additionally, we present a brief description of an example related to what is understood as a sustainable city, as well as a conceptual framework for civil engineers in order to integrate the concept of sustainable development into their activities. Next, we give some basic knowledge regarding composite indicators, to support decision-making. Finally, we introduce the case study in order to contextualize the related activities.

### 2.1. INTERNATIONAL CONTEXT ADDRESSING HUMAN SETTLEMENTS

The United Nations Human Settlements Programme (UN-Habitat) started in 1976 with the UN Conference on Human Settlements in Vancouver, Canada, at a time when the governments began seriously to perceive cities under their jurisdictions as “emerging futures” in their own right (United Nations Human Settlements Programme, 2016). There were two major outcomes of this path-breaking event. The first was the Vancouver Declaration, which urged both individual countries and the international community to commit to human settlement policies that combine spatial planning with elements of economic, social, and scientific thinking, in order to alleviate the worst conditions of “uncontrolled urbanization” within a framework of social justice. The second outcome, announced in a UN General Assembly document of December 1977, was the establishment of the United Nations Centre for Human Settlements as a focal point for coordinating activities within the UN (United Nations General Assembly, 1977).



**Figure 1** Relevant international events from 1976 to 2002 associated with human settlements.  
Source: United Nations Human Settlements Programme, 2016.

Two decades later, in June 1996, in Istanbul, the Second UN Conference on Human Settlements (Habitat II) further contributed to raising global awareness about urban and human settlements issues. As a remarkable turning point, this event marked the first time in a UN conference that NGOs and civil society organizations were invited to speak and participate in drafting recommendations (United Nations Human Settlements Programme, 2016). The main issues discussed were recognition of cities as the forefront in strategies for development, although poverty and poor housing conditions were increasing in incidence. In addition to this, citizen groups, community organizations, and NGOs were identified as important stakeholders to which more attention should be provided. Finally, the key role of the governance was highlighted, affirming that future governments would be enablers much more than providers.

At the beginning of the new millennium, world leaders gathered at the United Nations to shape a broad vision to fight poverty in its many dimensions. That vision, which was translated into eight Millennium Development Goals<sup>1</sup> (MDGs), remained the overarching development framework for the world for the next 15 years (United Nations, 2015). In this context, and regarding urbanization issues, a specific target (7.D) was included that aimed to achieve, by 2020, a significant improvement in the lives of at least 100 million slum dwellers. The result during the MDG period was a reduction of the proportion of urban population living in slums in the low-income regions, from approximately 39.4% in 2000 to 29.7% in 2014 (United Nations, 2015). In other words, between 2000 and 2014, more than 320 million people gained access to either improved water, improved sanitation, durable housing, or less crowded housing conditions, which means that the MDG target was largely surpassed. Although this target was met, the absolute numbers of urban residents living in slums continue to grow, partly due to accelerating urbanization, population growth, and the lack of appropriate land and housing policies. Over 880 million urban residents were estimated to live in slum conditions in 2015, compared to 792 million reported in 2000 and 689 million in 1990.



**Figure 2** International events regarding human settlement issues from 2002 to date. Source: United Nations Human Settlements Programme, 2016.

<sup>1</sup> More information related to the MDGs can be found at <http://www.un.org/millenniumgoals>.

In 2015, countries adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals<sup>2</sup> (SDGs). These SDGs aim to go further to end all forms of poverty. The new Goals are unique in that they call for action by all countries - low, high, and middle-income - to promote prosperity while protecting the planet. They recognize that ending poverty must go hand-in-hand with strategies that build economic growth and addresses a range of social needs including education, health, social protection, and job opportunities, while tackling climate change and environmental protection (United Nations). Specifically, Goal 11 sets out to “make cities inclusive, safe, resilient and sustainable”. In so doing, this goal proposes to focus on 10 Targets<sup>3</sup>.

In 2016, the United Nations Conference on Housing and Sustainable Urban Development took place in Quito, Ecuador. It was the first UN global summit on urbanization since the adoption of the 2030 Agenda for Sustainable Development the previous year. There, world leaders adopted the New Urban Agenda that set global standards of achievement in sustainable urban development, rethinking the way cities are built, managed, and lived in by combining cooperation with committed partners, relevant stakeholders, and urban actors at all levels of government as well as in the civil society and private sector (United Nations). Above all, this urban agenda should prescribe conditions that facilitate a shift towards more sustainable patterns of urbanization, seeking to achieve inclusive, people-centred, and sustainable global development. Therefore, the policies that emerge must be implementable, universal, sensitive, and relevant to the local context. They must be participatory and collaborative. They must be inclusive and recognize the rights of minorities and vulnerable groups. Above all, the policies must be sustainable (United Nations Human Settlements Programme, 2016).

## 2.2. URBANIZATION: GLOBAL OVERVIEW

It is remarkable that only one century ago, 20% of the world's population resided in urban areas. In lower-income countries, this proportion was just 5%. The world has been rapidly urbanized, and in 2008, for the first time in history, the urban population outnumbered the rural population. This milestone marked the advent of a new ‘urban millennium’. By 2050, it is expected that two-thirds of the world population will be living in urban areas (United Nations Human Settlements Programme, 2015).

Today, approximately half of humanity lives in cities (3.5 billion people). As a direct result of this situation, the world's cities occupy just 3% of the Earth's land, but account for 60% to 80% of energy consumption and 75% of carbon emissions. Thus, rapid urbanization is exerting pressure on fresh water supply, sewage, the living environment, and public health.

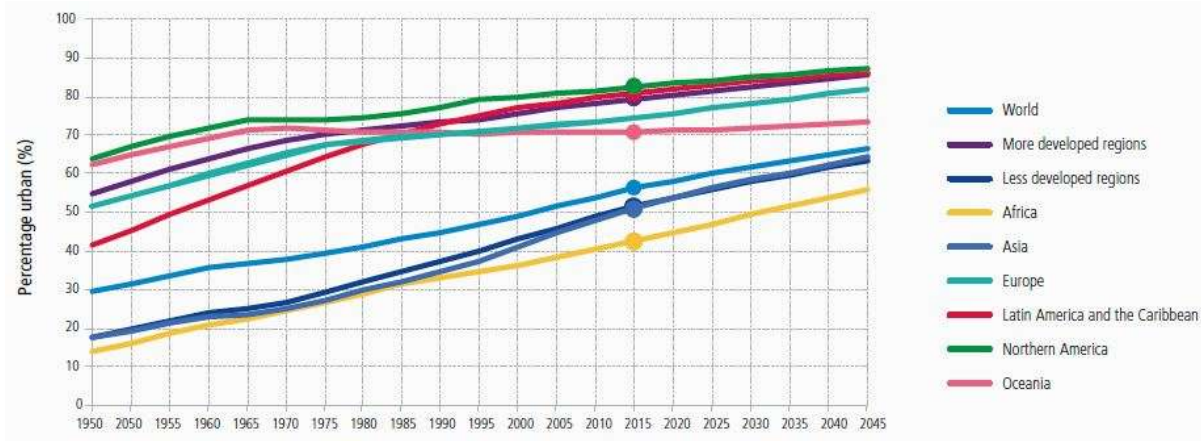
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<sup>2</sup> Detailed information regarding the SDGs can be consulted at <http://www.un.org/sustainabledevelopment>.

<sup>3</sup> A description of the 10 Targets can be found at <http://www.un.org/sustainabledevelopment/cities>.



However, the high density of cities can bring efficiency gains and technological innovation while reducing resource and energy consumption (United Nations). Urban planning requires a shift from viewing urbanization mainly as a problem, to seeing it as a powerful tool for development (United Nations Human Settlements Programme, 2015).



**Figure 3** Global trends in urbanization from 1950 to 2050 (% urban). Source: United Nations Human Settlements Programme, 2015.

Undoubtedly, cities are hubs for ideas, commerce, culture, science, productivity, social development, and much more. At their best, cities have enabled people to advance socially and economically. However, key current and new urban challenges have emerged over the years. Several examples are presented in the Habitat Global Activities Report (2015).

As a first example, the UN-Habitat report highlights that meteorological-based phenomena (i.e., storms, sea-level rises, inland flooding, droughts, etc.), associated with climate change have produced heavy losses, particularly among slum dwellers and the poorest populations (predominantly in the coastal areas). As a result, the average number of people killed as a consequence of these phenomena rose from 53,678 to 106,597, and the reported economic damage rose from an annual average of USD 55 billion to USD 156 billion, in the periods between 1994 - 2003 and 2003 - 2012. Thus, it is crucial to recognize that cities must also be part of the solution to the problem of climate change.

A second challenge is associated with the differentials in access to opportunities, income, consumption, location, information, and technology, which are now the norm rather than the exception. The report notes that gender inequalities persist in many countries and contexts (lower rates of secondary education, less access to decent employment, lower political representation, etc.). In addition to this, youth inequalities manifest in discrimination in access to education, differentiated levels of employment and livelihood opportunities, lack of participation in decision-making, and prejudice against sexual preferences. Finally, the report concludes that income inequalities combined with other forms of inequalities in society reinforce the deprivation faced by many groups and individuals based on gender, age,

ethnicity, location, disability, and other factors. Thus, inequalities generate an urban geography of concentrated disadvantage.

A last example detailed in the UN-Habitat report is the emergence of new forms of urban poverty, risk, and marginalization in high-income countries. An increasing number of urban residents in high-income countries experience, or are at risk of, poverty and/or social exclusion. In the European Union, 24% of the population falls in this category, with one out of ten people living in severe material deprivation, and 17% living on less than 60% of their country's average income. In many other cities, the persistence of intergenerational poverty and economic disadvantage is inextricably linked to location and place. However, in addition to these 'conventional' forms of poverty, new forms of social exclusion and marginalization are emerging, including 'infrastructure-poor', immigrant poverty, young people at risk, and vulnerable elderly, among others.

### 2.3. SUSTAINABLE CITIES AND SUSTAINABLE DEVELOPMENT IN CIVIL ENGINEERING

As defined in the report developed by BCNecologia (2010) regarding the city of Vitoria-Gasteiz (Spain), the city is an ecosystem, and contacts, regulation, exchange, and communication are the essence of its operation. In addition to this, the structure and the form of producing a city are considered to constitute the framework for the development of the interaction among citizens through their activities.

The BCNecologia report further points out that the city as a system increasingly requires the renewal of its functional structures, with the aim of building a city that is more sustainable and, at the same time, a model of knowledge. Thus, the objective lies in increasing the degree of organization of the territory as well as its potential for exchange of information, and decreasing the consumption of local resources - that is, of achieving the maximum efficiency of the urban system.

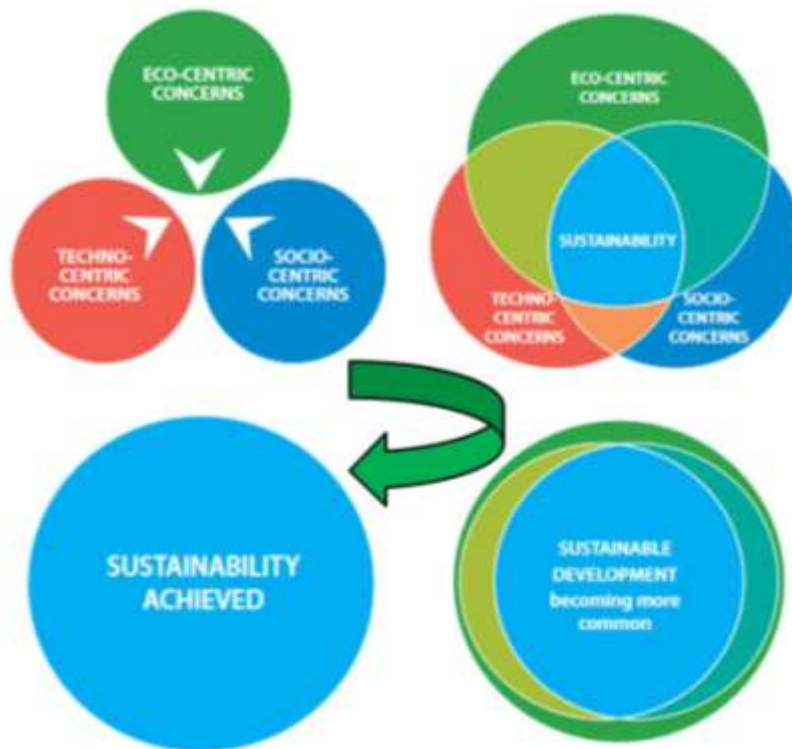
Against this background, the BCNecologia report presents a set of indicators with the aim to quantitatively and qualitatively assess the urbanization process of the studied city from an integral and systemic point of view with sustainability criteria. This indicator-based methodology deals with the large areas involved in the achievement of a sustainable city model from an ecosystem vision: occupation of the soil, public space and habitability, mobility and services, urban complexity, urban metabolism, green spaces, and urban biodiversity and social cohesion.



**Figure 4** Proposed conceptual framework to assess urbanization processes from a sustainable perspective. Source: Barcelona Urban Ecology Agency, 2010.

Sustainable development could become a guiding concept for engineers in the 21<sup>st</sup> century. In the context of civil engineering, this means that building infrastructure and providing associated services should be delivered to satisfy a broad diversity of interests and responsibilities (Fenner, et al., 2006). Engineers must continue to fulfil obligations to clients, ensure business viability, and strive for excellence and robustness in the application of engineering principles. In addition, by adopting a sustainable development perspective, they must extend their role to ensure that the real needs of all present end users are met, as well as recognizing impacts (and the opportunity for mitigation and benefit) on both the natural environment and future generations (Fenner, et al., 2006).

The term “sustainable development” is intrinsically value-laden and open to wide interpretation, with much debate about its definition. There is a real debate about whether the complexity of current problems is so great that it makes relying solely on technical solutions alone unrealistic. Nevertheless, engineers in their professional roles will still rely on applying technical solutions to problems, such as energy provision and adaptation to climate change. To get to such solutions, (civil) engineering practice needs to learn to handle a range of often unfamiliar non-technical challenges. The difficulty lies in finding ways to meet these challenges through practical, everyday engineering operations. Ideally, the sustainable development concept can be used simply to help define a wider problem boundary than those limits traditionally adopted by engineers. This then leads to the creation of a wider design space in which more holistically-conceived solutions can be formulated for any given problem.



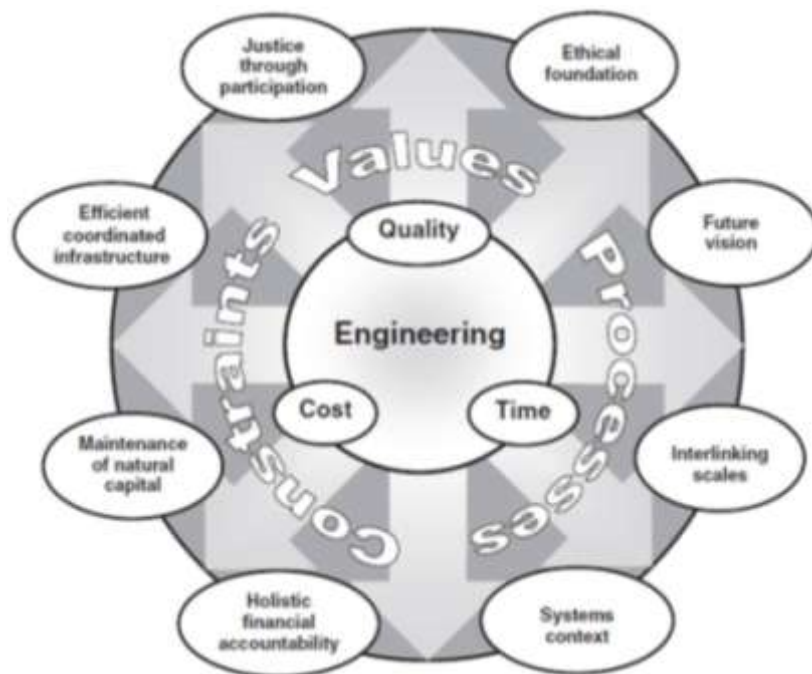
**Figure 5** Moving towards sustainable development. Source: The Royal Academy of Engineering, 2005.

As accurately explained in Fenner et al. (2006):

“This challenge may be highlighted by considering the three broad stages that a civil engineering project goes through: i) defining the problem, ii) choosing a solution, and iii) implementing it through design, construction and operation. Defining the problem requires recognition that most engineering services needed by society are framed by the whole socio - economic - environmental reality. At the other end of the process, design, construction and operation require the use the traditional deterministic mechanics and reductionist analytical techniques, which have been proved highly appropriate over the last three centuries for providing safe, working solutions, and rely completely on measurement. In between, choosing a solution requires making the transition between these two different sciences. To achieve this, more options need to be considered and evaluated, and more choice criteria developed, than are often adopted using the traditional approach. Furthermore, several of these criteria will not be conveniently measurable. Engineers will be forced to acknowledge that it is needed to apply values, as well as mathematics, to the trade-offs or compromises involved in the decision. These also need to be transparent and accountable to a wide constituency of interested parties.

Sustainable development is often discussed in terms of balancing the triple bottom line constraints of economic, social and environmental factors (see *Figure 5*). For many, this

remains vague. In response, and as examples, the Government of United Kingdom amplified these three pillars to a set of five key principles: i) living within environmental limits, ii) ensuring a strong, healthy and just society, iii) achieving a sustainable economy, iv) promoting good governance, and v) using sound science responsibly. On the other hand, the Royal Academy of Engineering has recently published a set of twelve guiding principles<sup>4</sup>. The RAE principles offer high-level advice such as: “Practice what you preach”, “Plan and manage effectively” and “Do things right, having decided on the right thing to do”. A last example, introduced by Fenner et al. (2006), provides a visualization of a knowledge map developed by Jabareen (2004). This last author provided a comprehensive representation of sustainable development thinking, encompassed in eight domains: ethics, fairness, urban form, preservation of natural capital, integrative management, global discourse, utopian ambition and financial management<sup>5</sup>.



**Figure 6** A sustainable framework for civil engineers. Source: Fenner et al., 2006.

<sup>4</sup> More information available at <http://www.raeng.org.uk/publications/other/engineering-for-sustainable-development>

<sup>5</sup> A detailed explanation of each domain can be found on Fenner, R. A., Ainger, C. M., Cruickshank, H. J., and Guthrie, P. M. 2006. “Widening Engineering Horizons: Addressing the Complexity of Sustainable Development”. In *Proceedings of the Institution of Civil Engineers - Engineering Sustainability* 159, pp 145-154.

## 2.4. INDICES AND INDICATORS AS TOOLS TO SUPPORT DECISION-MAKING

In general terms, an indicator is a quantitative or a qualitative measure derived from a series of observed facts that can reveal relative positions (e.g. of a country) in a given area. When evaluated at regular intervals, an indicator can point out the direction of change across different units and through time. In the context of policy analysis, indicators are useful for identifying trends and drawing attention to particular issues. They can also be helpful for setting policy priorities as well as for benchmarking or monitoring performance. On the other hand, a composite indicator is formed when individual indicators are compiled into a single index on the basis of an underlying model. The composite indicator should ideally measure multidimensional concepts that cannot be captured by a single indicator, e.g. competitiveness, industrialization, sustainability, single market integration, knowledge-based society, etc. (Nardo et al., 2005).

In terms of method and technique, index construction relies on a step-by-step procedure initially suggested by Nardo et al. (2005), which was subsequently applied to different conceptual frameworks<sup>6</sup> (e.g. water and sanitation sector). In this case study, the focus will be directed to some specific steps, but it should be highlighted that, ideally, the whole procedure must be considered for composite index construction. This complete procedure is detailed in Nardo et al. (2005); explanatory information regarding to each step is briefly given below.

**Step 1. Data selection.** Indicators should be selected on the basis of their analytical soundness, measurability, country coverage, relevance to the phenomenon being measured, and relationship to each other. Ideally, and as a previous step, a theoretical framework should be developed to provide the basis for the selection and combination of single indicators into a meaningful composite indicator under a fitness-for-purpose principle.

**Step 2. Normalization.** Indicators should be normalized to render them comparable. Attention needs to be paid to extreme values, which may influence subsequent steps in the process of building a composite indicator. Skewed data should also be identified and accounted for.

Normalization is required prior to any data aggregation, as the indicators in a data set often have different measurement units. As a normalization example, we present the so-called “re-scaling” or “min-max” process, in which indicators are normalized to have an identical range [0, 1] by subtracting the minimum value and dividing by the range of the indicator values. In this sense, attention should be paid to extreme values or “outliers”, as they could distort the transformed indicator. On the other hand, “min-max” normalization could widen the range of

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<sup>6</sup> Detailed examples for composite indicator construction are given in Flores-Baquero et al. (2016) and Giné-Garriga & Pérez-Foguet (2010; 2013).



indicators lying within a small interval, increasing the effect on the composite indicator. Mathematically, it is represented by the following expressions:

$$I_{qc}^t = \frac{x_{qc}^t - \min_c(x_q^t)}{\max_c(x_q^t) - \min_c(x_q^t)} \quad (\text{eq. 1})$$

where  $I_{qc}^t$  is the normalized indicator value,  $x_{qc}^t$  the value of the sample indicator for a time  $t$  of analysis,  $\max_c(x_q^t)$  the maximum value of the sample indicator for a time  $t$  of analysis, and  $\min_c(x_q^t)$  the minimum value of the sample indicator for a time  $t$  of analysis.

The above formula addresses a "more is better" indicator. However, as the opposite might also be true, the indicator is a "less is better" type (e.g. less concentration of immigrants in a given area is better in terms of integrated society). In this sense, the first expression should take the following form:

$$I_{qc}^t = 1 - \frac{x_{qc}^t - \min_c(x_q^t)}{\max_c(x_q^t) - \min_c(x_q^t)} \quad (\text{eq. 2})$$

**Step 3. Weights and aggregation.** Indicators should be aggregated and weighted according to the underlying theoretical framework. Additionally, correlation and compensability issues among indicators need to be considered and either corrected for, or treated as features of, the phenomenon that will be retained in the analysis.

For weighting methodologies, there are several numerical and participatory processes with the aim to assess the relative importance among the indicators and composite indicators on hand. In this sense, there is the possibility of either providing equal weights to the considered variables or of using any of the existing methods to define the different weights. In terms of use, equal weights are considered more transparent when dealing with composite indicators, and they facilitate interpretation of the results. On the other hand, different weights might be more adjusted to reality, but the results are more difficult to interpret accurately.

Two alternatives are presented for the aggregation methods, although more possibilities are available. These are the additive aggregation (arithmetic mean calculation) and geometric aggregation (geometric mean calculation).

The additive aggregation method has the advantage of compensating the final value of a composite indicator. However, this compensation comes with the loss of being able to clearly communicate the information. That is, a composite indicator might have a desirable value as a result of two indicators. This value could be the result of a very high value of one of the

indicators and an undesirable value of the other. By using this aggregation method, this information could not be properly transmitted, and there could be comparative errors among the contexts that are assessed. The mathematical expression behind this method can be represented as follows:

$$CI = \frac{1}{n} \sum_{i=1}^n w_i \cdot X_i \quad (\text{eq. 3})$$

where CI is the composite indicator value and  $w_i$  the weight assigned to the  $n$  indicators considered  $X_i$ .

The geometric aggregation method, on the other hand, implies penalizing the dispersion of the variables that are aggregated. In this sense, and in order to achieve high values of the composite indicator, it is necessary to have high values in all considered indicators. Contrary, one of the drawbacks is that if one of the indicators is zero, the geometric mean will be zero as well. Mathematically, this method is expressed as follows:

$$CI = \prod_{i=1}^n X_i^{w_i} \quad (\text{eq. 4})$$

As mentioned above, one of the advantages of the additive aggregation is that it allows the compensation between different indicators, particularly the compensation of a null value in any of the variables to be aggregated. In addition to this, it is conceptually simpler, both at the level of implementation and for the interpretation of the results obtained. However, this method hides the existence of very low values (compensation), which is not recommended in some cases.

Against this background, when dealing with composite indicator construction, the different aspects described above should be taken into consideration. It is not possible to point out a better methodology, as it depends of the potential use of the composite indicator, the public to whom the results will be transmitted, etc. In this sense, it is recommended whenever possible to apply a comparison exercise in order to assess the impacts of the selected option.

## 2.5. CASE STUDY OF BARCELONA

Barcelona is the capital and largest city of Catalonia, an autonomous community in Spain, and the country's second most populous municipality, with a population of 1.6 million within the city limits. Its urban area extends beyond the administrative city limits, with a population of around 4.7 million people, making it the sixth most populous urban area in the European Union. It is the largest metropolis on the Mediterranean Sea, located on the coast between



the mouths of the rivers Llobregat and Besòs, and it is bounded to the west by the Serra de Collserola mountain range, the tallest peak of which is 512 meters high. Barcelona is divided into 10 districts. These are administrated by a councillor designated by the main city council, and each of them has some competences relating to issues such as urbanism or infrastructure in their area. The current division of the city into different districts was approved in 1984. In 2009, a new division of 73 neighbourhoods was implemented (the 10 districts are still in use), a division that was done to offer a better service from the City Council.



**Figure 7** Division of Barcelona city into its different districts. Source: Own elaboration, from [w33.bcn.cat](http://w33.bcn.cat).

Urban development in Barcelona in recent years, its commitment to design and innovation, and its linking of urbanism with ecological values and sustainability have made Barcelona one of the leading European cities in the urban area. This fact has been recognized with numerous awards and distinctions, such as the Prince of Wales Award for Urbanism at Harvard University in 1990 and the Royal Institute of British Architects Gold Medal in 1999. The work done and the awards received have led to talk of a "Barcelona Model" in urbanism, which has served as a guide for many cities that have undertaken similar paths.

Nevertheless, Barcelona is still struggling with aspects related to sustainability and the entry into a society of information and knowledge. The compact and diverse city model is the one that best positions itself in this process towards sustainability in the information age. This model permits an increase in the complexity of its internal parts, which is the basis for a cohesive social life and a competitive economic platform. At the same time, the objective is to save land, energy, and material resources, and to contribute to the preservation of agricultural and natural systems.



**Figure 8** Main mobility arteries in Barcelona, where Ronda de Dalt is located at the upper side.

Source: <http://www.ub.edu/biometa/lugarcelebracion.html>.

Nowadays, several projects are taking place in Barcelona to achieve a more sustainable and cohesive city. Specifically, this case study presents the project of the Ronda de Dalt, which is a mobility artery that crosses several districts of the city (see *Figure 8*). Different neighbourhoods of these districts are affected by the noise and pollution level generated by the Ronda de Dalt. The Plenary of the Municipal Council agreed that it was necessary to improve this situation, and to help humanize the urban surroundings of the Ronda de Dalt. Changing the perception that the mountain districts have of it, as well as improving the environmental and acoustic conditions of connecting the districts of Gràcia, Horta-Guinardó, and Nou Barris with the rest of the city, are primary goals. The main idea is to cover some sections of the Ronda de Dalt, with the aim of recovering and creating new spaces to increase urban greenery and public facilities, as well as to boost civic, neighbourhood, and commercial activities and to mobilize resources and investments in the area.

### 3. CLASS ACTIVITY

The proposed class activity aims to encourage a discussion beyond those technical and economic aspects that are usually considered during the design of a project. These further aspects are not intended to replace the traditional cost/time/quality approach, which must be still regarded as essential ingredients in successful projects. However, the traditional engineering requirements have evolved to encompass a broader range of considerations.

These are necessary to enable civil engineering to contribute effectively to sustainable development.

This class activity is divided in two sections or blocks, with a total duration of two hours. For the methodology, we propose working in small groups (i.e. 3 to 4 people); further details are given in each block of the activity.

### **Class activity: Block I**

In the first part of the class activity, programmed for one hour of work, students should read the paper titled “Widening engineering horizons: addressing the complexity of sustainable development” (Fenner et al., 2006).

In small groups, students should first read the eight dimensions detailed within the academic article and then select and justify which one of those dimensions appears more relevant to them. For this, 20 minutes will be given for the lecture and 10 to 15 minutes, to discuss and select the most relevant dimension from their point of view.

Finally, the student should share the group points of view in a general debate that should be expected to last between 25 and 30 minutes.

### **Class activity: Block II**

This second part is expected to take another hour of work. We suggest that the same working groups are maintained. As in Block I, the idea is to encourage discussion, first in each group and then with all participants for closing the activity, with 30 minutes allotted for each discussion.

During the proposed activity, *Table 1* should be filled out. In this table, several indicators are identified, with a short definition of each one. The proposed indicators have been extracted from those detailed in the report developed by BCNecologia (2010). We do not recommend providing the reference source to the students; rather, the teacher should highlight that these indicators might be used in decision making, both for designing a project and for prioritizing where to execute it, such as for the example of Barcelona (i.e. which section of the Ronda de Dalt to cover first). The objective of this exercise is to detail the direct and indirect impacts related to a high value of the proposed indicators. A low value would have the opposite impacts, so it is avoided as not to be redundant.

**Table 1** Proposed indicators on which the discussion regarding potential direct and indirect impacts should be based.

Indicator	Definition	Direct impacts	Indirect impacts
Population density	Existing population per hectare of land		
Aging index	Quantitative relationship between older and younger people in a given territory		
Foreign population	Spatial distribution of the immigrant population, taking into account their number and that of the total population		
Higher education	People with higher studies, taking into account their number and that of the total population		
Protected housing	Access to housing for those people with less acquisitive level		
Public transport	Access to an affordable and effective public transport network		
Green spaces	Proximity to green areas in a given part of a city		

### 3.1. SOLUTION AND EVALUATION CRITERIA

#### Class activity solution: Block I

There is no a specific solution for this activity, as it is an open-answer one. The main idea is to give the students the chance to select the dimension they consider more relevant and then, more importantly, to share and defend their arguments.

As a support for the professor, who should be the moderator for this activity, we are providing extra guidance (extracted from Fenner et al.; 2006):

- An ethical foundation and justice through participation lead to **new values** to apply when making engineering decisions;
- A future vision, interlinking scales, and system context provide the basis for **new processes** that can be used to better define problems and to offer guidance in choosing appropriate strategies for development;
- Holistic financial accountability, maintenance of natural capital, and efficient provision of coordinated infrastructure provide **new constraints** in formulating solutions.

In the case all groups have selected same dimension, the discussion might be directed to expose the reasons for not choosing any other dimensions as the most relevant ones.

## Class activity solution: Block II

To evaluate the second part of the activity, we have provided several impacts when the indicator at hand acquires a high value (*Table 2*). Note, however, that these solutions are only provided to offer guidance for supporting the general discussion.

**Table 2** Examples of potential direct and indirect impacts regarding the proposed indicators.

INDICATOR	DIRECT IMPACTS	INDIRECT IMPACTS
Population density	<ul style="list-style-type: none"> <li>- Congestion in terms of public space and services</li> <li>- Compactness of the city</li> </ul>	<ul style="list-style-type: none"> <li>- In some way, it represents a cost in terms of time when accessing several services. Less space is associated with each individual, which might cause health problems</li> <li>- Less consumption of resources (i.e. transport to provide food). In disperse areas, it would be less efficient</li> </ul>
Aging index	<ul style="list-style-type: none"> <li>- Less cohesion of diverse age groups through the contact in the same physical space</li> <li>- Changes in social demands (more health and social assistance)</li> </ul>	<ul style="list-style-type: none"> <li>- Loss of intergenerational experience transfers</li> <li>- Potential losses in several socio-economic activities</li> </ul>
Foreign population	<ul style="list-style-type: none"> <li>- Less cohesion of groups from different countries through the contact in the same physical space</li> </ul>	<ul style="list-style-type: none"> <li>- Prevalence of existing stereotypes</li> </ul>
Higher education	<ul style="list-style-type: none"> <li>- Less cohesion of the groups of diverse incomes through the contact in the same physical space. Less diverse groups of population</li> </ul>	<ul style="list-style-type: none"> <li>- Potential generation of new stereotypes associated to income aspects</li> </ul>
Protected housing	<ul style="list-style-type: none"> <li>- Mitigation of the spatial segregation within the city</li> </ul>	<ul style="list-style-type: none"> <li>- Increased social cohesion</li> </ul>
Public transport	<ul style="list-style-type: none"> <li>- Facility to improve collective mobility</li> <li>- Less atmospheric and acoustic pollution</li> </ul>	<ul style="list-style-type: none"> <li>- Expenditure on transport is possibly lower than that for supporting use of cars</li> <li>- Positive effects on health</li> </ul>
Green spaces	<ul style="list-style-type: none"> <li>- Increased recreation activities</li> <li>- Less atmospheric pollution</li> <li>- Maintenance of urban ecosystems and biodiversity</li> </ul>	<ul style="list-style-type: none"> <li>- Increased social cohesion</li> <li>- Positive effects on health</li> <li>- Satisfaction of human's "need of nature"</li> </ul>

## Evaluation criteria

In order to provide the students with an objective and transparent evaluation system, we suggest using the provided rubric (see *Annex IX*), which details: i) the knowledge that students are expected to acquire, and ii) the criteria that will be used to evaluate the content of the resolution associated with the proposed activities.

Before carrying out these activities, the rubric must be shared among the students with the aim to inform which contents will be evaluated. Thus, some guidance is given to students to allow them to carry out the proposed activities.

Specifically, to evaluate both Blocks I and II, each group must submit a written document answering the questions raised. These answers will be evaluated based on the proposed rubric. However, the teacher is free to choose an alternative evaluation method if she/he considers it more appropriate.

#### 4. HOMEWORK ACTIVITY

This activity is organized into two different complementary parts. The first one deals with the construction of a composite indicator as a tool to support decision-making. The second falls on proposing a technical design by using pre-stressed concrete solutions. In both cases, the requested activities will be applied to the context of Barcelona, which was introduced previously.

The entire activity will be developed in small groups (i.e. 3 to 4 people). We recommend using the same groups created in classroom activity, in order to facilitate evaluation. While the first part requires about 2 - 4 hours of work, the second part might be developed over an academic semester. In this sense, and with the constant support of the professor, this last part might be associated with the Project-Based Learning (PBL) methodology. PBL is a teaching method in which students gain knowledge and skills by working for an extended period of time, during which they are invited to investigate and respond to an authentic, engaging, and complex question, problem, or challenge. Therefore, students will develop the generic competence of teamwork and, in addition, they will experience a short of professional environment.

Specifically, in terms of methodology, the achievement of this activity is organized through several workshops, which are parallel to the progression of course contents (for an applied example, see *Annex X*). In these workshops, the professor should give a guided presentation at the beginning of the session, and the students should work within their teams to develop the project. Some specific objectives are advised at the beginning of each session. Thus, students are expected to progress in their projects by setting their own learning pace. Briefly, and after receiving the topographic drawing, students should establish a list of contour conditions. Considering the different contour conditions, students should define the plan view and elevation of the pedestrian covering. In addition, students should predefine the dimensions of the structural elements (deck, piles, and abutments). Afterwards, students should develop a structural model in order to obtain the envelopes of axial forces, shear forces, and bending moments for the ultimate limit state (ULS) and



serviceability limit state (SLS) combinations. Then, team groups should calculate the internal steel reinforcement and the pre-stressed reinforcement required to achieve the different ULS and SLS. Finally, a bill of materials required for constructing the pedestrian covering should be included in the report, considering the following items: concrete, formwork, pre-stressing reinforcement, and internal steel reinforcement. On the final day of class, the students might present a short summary of the rationale of action area selection and the structural solution, showing the plan view, the elevation, and the transverse section together with the total bill of quantities of the structure.

### Homework activity: Part I

In this first part, students are required to design a composite indicator as a decision tool to prioritize which section of the Ronda de Dalt should be covered first. In addition, students are required to reflect on and then link their solutions from the perspective of the deontological code of engineers (code of ethics) provided in *Annex XI*.

**Table 3** Division of selected districts and neighbourhoods into different groups.

Group	District	Affected neighbourhoods
I	Horta - Guinardó	La Vall d'Hebron Horta
II	Nou Barris	La Guineueta Canyelles
III	Nou Barris	Les Roquetes Verdun
IV	Nou Barris	La Prosperitat La Trinitat Nova

As pointed out by the Plenary of the Municipal Council, the districts that have a greater need for urgent intervention are Horta-Guinardó and Nou Barris<sup>7</sup>. Considering the location of the Ronda de Dalt and the neighbourhoods of these districts, it is possible to define four separate groups (*Table 3*). The potential intervention will join the neighbourhoods of these groups.

To design the composite indicator, the different steps introduced in section 2.4 should be followed. At least one set of indicators should be used, as well as a weighting methodology and an aggregation method. Regarding this last point, a hierarchical composite indicator could be developed by using several partial indices. Indicators and data are available in

<sup>7</sup> Related news on this regard can be found at: <http://mobilitat.ajuntament.barcelona.cat/es/noticia/impulso-a-la-cobertura-de-la-ronda-de-dalt>; <http://mobilitat.ajuntament.barcelona.cat/es/noticia/la-cobertura-de-la-ronda-de-dalt-cada-dia-mzas-cerca>

*Annexes from I to VIII.* Additional data might be used from the Barcelona Council website (<http://www.bcn.cat/estadistica/angles/dades/barris/index.htm>).

Finally, students should provide a discussion about the designed composite indicator, including the reasons for selecting the indicators and methods employed.

### **Homework activity: Part II**

Once the location of the area of the Ronda de Dalt to be covered is selected, according to the composite indicator developed, the constructive solution of the project must be developed. In this sense, several aspects should be taken into consideration.

The City Council provides the topography of the area at a scale of 1:1000 (see *Annex XII*), and sets as a condition that the structure should be independent of the existing one. The minimum gauge of Ronda de Dalt and the ramps will be 5.0 m. A specific study considering the slope of the ramps and the gauge will allow the area that will be covered in the project to be defined.

Since the activity is designed for a pre-stressed concrete course, the slab will be designed in a pre-stressed concrete solution (in situ or precast). The cross-section can be a solid slab, a lightened slab, or a box girder, depending on the designer's decision. The slab depth can be constant or variable.

The covered area will be dedicated to public space and a possible landscaped area, which will require an earth filling of approximately 1.50 m thickness.

The slab will follow a two-cantilever scheme, being supported in a wall along the central median strip of the Ronda de Dalt.

Loads should be considered according to the Spanish Code of Actions in road bridges (IAP-11). This document can be downloaded from the Ministerio de Fomento<sup>8</sup> (Spanish Ministry of Development). In a simplified manner, the live load can be assumed with a uniform value of 15 kN/m<sup>2</sup>. The horizontal, wind, and thermal loads will be neglected in this activity.

In case a post-tensioned solution is adopted, the system employed will be according an existing commercial catalogue (i.e. Mk4, Diwidag, Stronghold, VSL, etc.), active anchorages will be placed in one or both ends, and their dimensions will set be according to the catalogue. The mechanical anchorage will have a 5 mm wedge penetration,  $\mu = 0.21$ ,  $k/\mu = 0.008\text{m}^{-1}$ .

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<sup>8</sup> <https://www.fomento.gob.es/NR/rdonlyres/2E268DB6-87AC-41C9-A331-32C63C25195C/111523/0820303.pdf>



The quality control will be intense.

All calculations of the homework will be according to the Spanish Concrete Code (EHE-08<sup>9</sup> or Eurocode-2). Assumptions should be explained throughout the solution.

Points that are required to be included:

A) Pre-design of the pre-stressed slab

- Define the geometry of the solution through a plan and elevation drawing, placing intermediate supports using the topography and Autocad software (*Annex XII*). The presentation format should be clear enough to submit to the City Council;
- Pre-design of the cross section of the cover slab, including a sketch of it;
- Obtain the envelope of axial, shear forces, and bending moments of the ultimate limit state (ULS) and serviceability limit states (SLS) combinations;
- Obtain the mechanical properties of the slab cross-section.

B) Design of the pre-stressed slab

- Pre-design the pre-stressing force and the eccentricity required in the support section to satisfy the cracking limit state;
- Obtain the pre-stressing force at the mechanical anchorage, the pre-stressing area, the number of tendons, and the diameter of the duct. For the support section (end of cantilever), draw the Magnel diagram and propose a solution for this section in terms of “P” and “e”. Based on the results obtained up to this point, reflect and discuss about the suitability of this section for resisting external loads. Draw the layout of the active reinforcement in several sections as well as the layout of the equivalent tendon, verifying that it is within the approximate central kern;
- Obtain the short- and long-term stresses for at least 20 sections of the deck, and verify cracking SLS. It is recommended to calculate the stress state in all sections equidistant from each other 0.50 m;

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<sup>9</sup>[https://www.fomento.gob.es/MFOM/LANG\\_CASTELLANO/ORGANOS\\_COLEGIADOS/MASORGANOS/CPH/instrucciones/EHE\\_es](https://www.fomento.gob.es/MFOM/LANG_CASTELLANO/ORGANOS_COLEGIADOS/MASORGANOS/CPH/instrucciones/EHE_es)

- Estimate the cable elongation, as well as the vertical displacement due to the pre-stressing force at the free end of the cantilever. Estimate the long-term vertical displacement as well;
- Check the flexural ULS in the worst section, arranging the necessary longitudinal passive reinforcements;
- Check the ULS of shear, calculating the necessary transverse reinforcements;
- Select the appropriate anchorage devices, checking the stresses in the concrete under them and define the required passive reinforcement;
- Present drawings of the overall solution geometry and drawings of the passive and active reinforcements.

C) Obtain the bill of quantities for the design project

#### 4.1. SOLUTION AND EVALUATION CRITERIA

##### **Homework activity solution: Part I**

First, indicators used for the composite indicator construction are presented (see *Table 4*). Additionally, indicator definitions and the composite indicator structure are detailed as well. The rationale of the general index, named “Priority Index”, is to assess those socio-economic aspects of the neighbourhoods at hand. Access to public services is evaluated as well. As covering the Ronda de Dalt is designed to provide a green connection between the neighbourhoods, environmental aspects should not be considered, in order to simplify the composite indicator. Nevertheless, the proposal might be amplified with those indicators and aspects that the students consider relevant.

As the selected indicators are measured in different units, a normalization process is carried out in order to be able to work with them all together. The indicators of population density and population income index have been chosen to illustrate the methodology employed. Thus, neighbourhoods with a higher density and low income (population income index; “RFD” for Spanish “Renta Familiar Disponible”) will have lower values (see *equations 1* and *2*). The normalization of these indicators is calculated for the La Guineueta neighbourhood, and the results for the remaining ones are presented in *Table 5*.

$$\text{Density}_{\text{norm}} = 1 - \frac{x_{qc}^t - \min_c(x_q^t)}{\max(x_q^t) - \min_c(x_q^t)} = \frac{674-622}{957-622} = 0.54$$

$$\text{RFD}_{\text{norm}} = \frac{x_{qc}^t - \min_c(x_q^t)}{\max(x_q^t) - \min_c(x_q^t)} = \frac{55.9-47.8}{92.6-47.8} = 0.36$$

**Table 4** Structure of the “Priority Index” in indicators and partial and general indices.

General Index	Partial indices	Indicators	Definition
PRIORITY INDEX	Social aspects	S.1. Density	inhabitants / residential area
		S.2. Percentage of immigrants	Foreign population / total population
		S.3. Aging index	(People aged 65 / people aged 15)*100
		S.4. Percentage of people with disabilities	People with disabilities / total population
	Economic aspects	E.1. Population income index (RFD)	Average level of family income available per capita of the inhabitants of the neighbourhood in relation to the average of Barcelona (Index 100)
		E.2. Registered unemployment	Percentage of unemployed / population between 16 and 65 (inter-annual variation)
		E.3. Higher education	Population with higher education / population over 16
	Public and cultural equipment	P.1. Public libraries	Absolute value
		P.2. Usage of public equipment area	(Area of public equipment usage / total area)*100

**Table 5** Results associated to the normalization process for density and RFD indicators.

Neighbourhood	Density	Density <sub>norm.</sub>	RFD	RFD <sub>norm.</sub>
La Vall d'Hebron	732	0.42	92.6	1.00
Horta	419	1.00	80.9	0.80
La Guineueta	674	0.53	55.9	0.36
Canyelles	622	0.62	55.6	0.35
Les Roquetes	846	0.21	47.8	0.21
Verdun	859	0.18	55.4	0.35
La Prosperitat	957	0.00	54.0	0.32
La Trinitat Nova	577	0.71	35.6	0.00

The results related to all normalized indicators are presented below:

**Table 6** Results associated with the normalization process for all indicators.

Neighbourhood	S.1	S.2	S.3	S.4	E.1	E.2	E.3	P.1	P.2
La Vall d'Hebron	0.42	0.73	0.25	1.00	1.00	0.00	1.00	0.00	1.00
Horta	1.00	0.60	0.24	0.83	0.80	1.00	0.74	1.00	0.18
La Guineueta	0.53	0.80	0.00	0.18	0.36	0.68	0.57	1.00	0.39
Canyelles	0.62	1.00	0.07	0.00	0.35	0.68	0.22	1.00	0.48
Les Roquetes	0.21	0.00	1.00	0.47	0.21	0.68	0.06	0.00	0.18
Verdun	0.18	0.07	0.51	0.46	0.35	0.68	0.20	1.00	0.00
La Prosperitat	0.00	0.40	0.25	0.69	0.32	0.83	0.27	0.00	0.17
La Trinitat Nova	0.64	0.07	0.95	0.16	0.00	0.77	0.00	0.00	0.29

At this point, it is noteworthy to mention that an alternative method is to take into account the tendency of the indicators, instead of a fixed image of 2016 (as for the example). Considering time aspects might provide a different analysis and, in consequence, lead to making different decisions. This has been done for the indicator related to the registered unemployment.

**Table 7** Structure of the “Priority Index”: i) indicators and partial and general indices; ii) weight assignment; and iii) aggregation methodology.

General Index		Partial indices		Indicators
PRIORITY INDEX	Equal weights & Geometric aggregation	Social aspects	Equal weights & Additive aggregation	S.1. Density
				S.2. Percentage of immigrants
				S.3. Aging index
				S.4. Percentage of people with disabilities
		Economic aspects	Equal weights & Additive aggregation	E.1. Population income index (RFD)
				E.2. Registered unemployment
				E.3. Higher education
		Public and cultural equipment	Equal weights & Additive aggregation	P.1. Public libraries
				P.2. Usage of public equipment area

The next step for composite indicator construction is to assign weights and to select the aggregation methodology. For the first aspect, equal weights are chosen in this example for

both indicators and partial indices aggregation. However, it is possible to use different weights depending on the priorities of the designer. In relation to the second aspect, first, and additive aggregation is selected to partial indices construction. The main reason falls on the existence of zero values as a result of the normalized process. In this way, compensation among indicators is allowed. Finally, a geometric aggregation is employed for general index construction. As a first compensation has already been carried out, the main idea is to penalize those partial indices that are already low. A representation of all these considerations is shown in *Table 7*.

Finally, results regarding partial and general indices are presented in *Table 8*. As it can be seen, the neighbourhood of Les Roquetes would be the candidate where to execute the covering of the section of the Ronda de Dalt, according to the composite indicator developed (PI = 0.23). However, the execution of the project aims to join two neighbourhoods. Based on this, and taking into account the values of the grouped neighbourhoods (see *Table 3*), the decision would fall on La Prosperitat and La Trinitat Nova (PI = 0.24 and PI = 0.26, respectively).

**Table 8** Results regarding partial and general indexes. Lower values indicate a higher priority as reflected in the ranking (whereby 1 indicates the highest priority, and 8, the lowest one).

Neighbourhood	Social aspects	Economic aspects	Public and cultural equipment	PRIORITY INDEX (PI)	Ranking
La Vall d'Hebron	0.60	0.67	0.50	0.59	7
Horta	0.67	0.85	0.59	0.69	8
La Guineueta	0.38	0.53	0.69	0.52	6
Canyelles	0.42	0.42	0.74	0.51	5
Les Roquetes	0.42	0.32	0.09	0.23	1
Verdun	0.31	0.41	0.50	0.40	4
La Prosperitat	0.34	0.48	0.09	0.24	2
La Trinitat Nova	0.47	0.26	0.15	0.26	3

The link with the deontological code of engineering (*Annex IX*) will depend on the selected indicators. In this case, for example, designing and using the proposed index would respect the first two principles of the ethics code:

- Enhancement of human welfare and the environment;
- Honesty and impartiality, serving with fidelity the public.

In addition, some of the fundamental canons are followed as well:

- Comply with the principles of sustainable development;
- Perform services only in areas of their competence;
- Issue public statements only in an objective and truthful manner;
- Avoid conflicts of interest.

### Homework activity solution: Part II

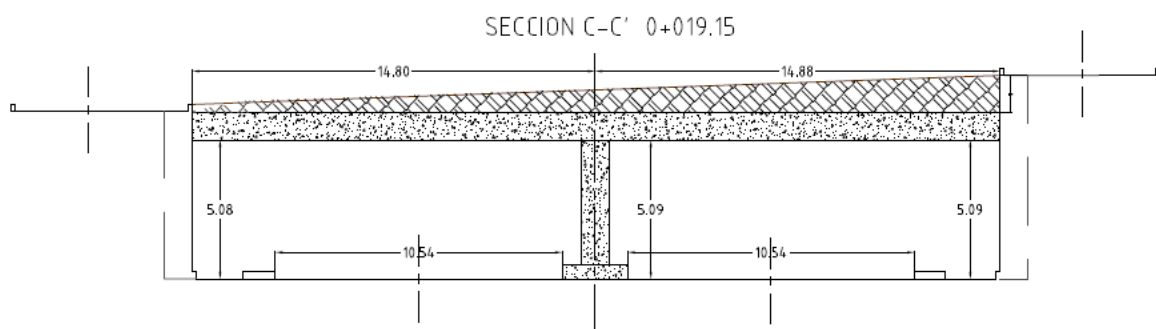
Once the neighbourhoods have been selected, the next decision is which area should be covered. In this case, the section between Via Julia and Carrer de Fenals has been chosen. It should be noted that, due to the existence of two ramps (Exit 2 of Ronda de Dalt), it will not be possible to cover the whole section mentioned above. A specific study will be performed by analyzing the elevation.

In the following pages, a step-by-step solution is provided with respect to the most relevant aspects and calculations. In *Annex XIII*, a detailed consultation of all calculations can be done. The students are expected to provide a similar solution for activity evaluation.

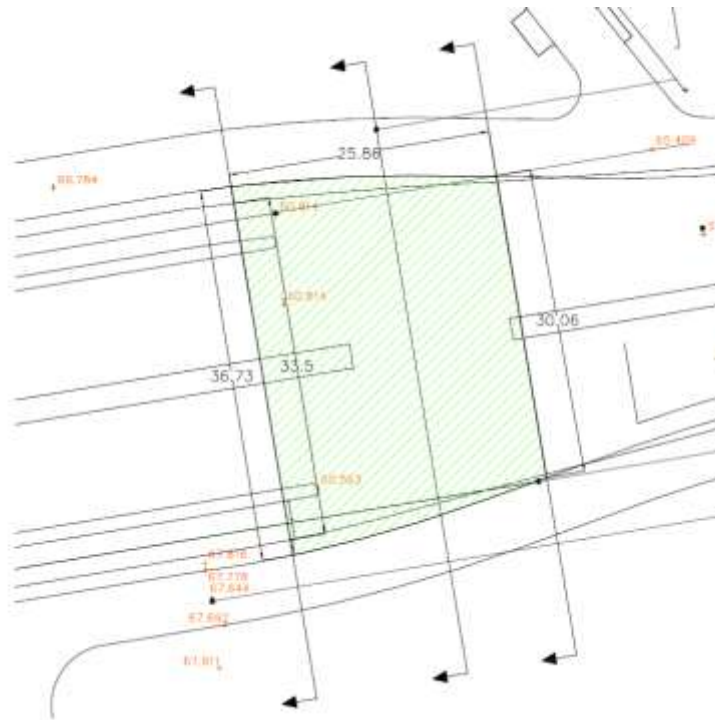
#### A) Pre-design of the pre-stressed slab

- Geometry of the solution.

Figures 9 and 10 show a scheme of the drawings included in *Annex XIV*.



**Figure 9** Transversal section.



**Figure 10** Plan view of the area to cover.

- Pre-design of the cross section of the cover slab, including a sketch of it.

The pre-stressed post-tensioned slab will have a cantilever scheme with a span of 14.85 m. The slab will be 1.2 m thick and will be lightened with EPS blocks with a cross section of  $0.80 \times 0.80$  m and a spacing of 1.3 m between axes. This is not the only possible solution, and students could select another one.

- Envelope of axial, shear forces, and bending moments of ULS and SLS combinations

The loads considered in the calculations according to the guidelines of IAP-11 are:

Concrete self-weight:  $\gamma_c = 25 \text{ kN/m}^3$

Soil fill weight (dead load):  $\gamma_{\text{soil}} = 20 \text{ kN/m}^3$ , 1.5 m thickness

Live load:  $Q_{k1}\text{-IAP11} = 5 \text{ kN/m}^2$

Combination of actions:

### Ultimate limit states

Permanent or temporary situations:

$$\sum_{j>1}^n \gamma_{G,j} G_{k,j} + \gamma_P P_k + \gamma_{Q,1} Q_{k,1}$$

### Serviceability limit states

Only persistent design situations are considered for these limit states.

Unlikely or characteristic combination:

$$\sum_{j>1}^n \gamma_{G,j} G_{k,j} + \gamma_P P_k + \gamma_{Q,1} Q_{k,1}$$

Frequent combination:

$$\sum_{j>1}^n \gamma_{G,j} G_{k,j} + \gamma_P P_k + \psi_{1,1} \gamma_{Q,1} Q_{k,1}$$

Quasi-permanent combination:

$$\sum_{j>1}^n \gamma_{G,j} G_{k,j} + \gamma_P P_k + \sum_{i>1}^n \psi_{2,i} \gamma_{Q,i} Q_{k,i}$$

The representative values of the actions have been calculated according to IAP-11.

Table 9 shows the total load of each combination and the maximum bending moments in the most unfavourable section of the slab (e.g., at the connection with the support).

**Table 9** Load values and bending moments at the support connection section.

LOAD VALUES AND BENDING MOMENTS			
Ultimate limit state (ULS)			
$q_{ELU}$ (kN/m)	98.5	$M_{ELU}$ (kN.m)	10,855.22
Serviceability limit states (SLS)			
$q_{PP}$ (kN/m)	23.0	$M_{PP}$ (kN.m)	-2,536.01
$q_{p-p}$ (kN/m)	68.5	$M_{p-p}$ (kN.m)	-7,552.90
$q_{FREC}$ (kN/m)	54.6	$M_{FREC}$ (kN.m)	-7,122.88
$q_{cp}$ (kN/m)	62.0	$M_{cp}$ (kN.m)	-6,836.20



- Mechanical properties of the slab cross-section.

$$A_c = 0.92 \text{ m}^2, I_c = 0.153 \text{ m}^4, v = 0.6\text{m}, v' = -0.6 \text{ m}$$

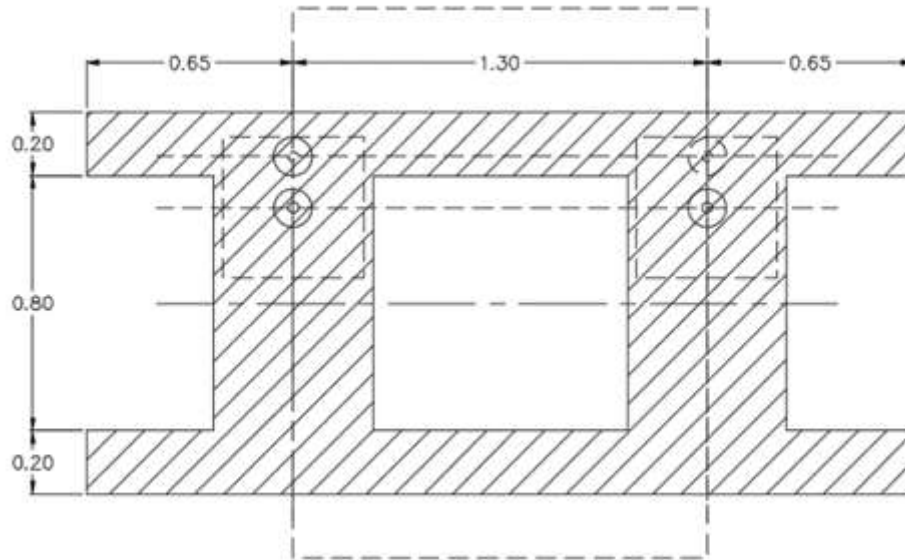


Figure 11 Slab section.

### Materials

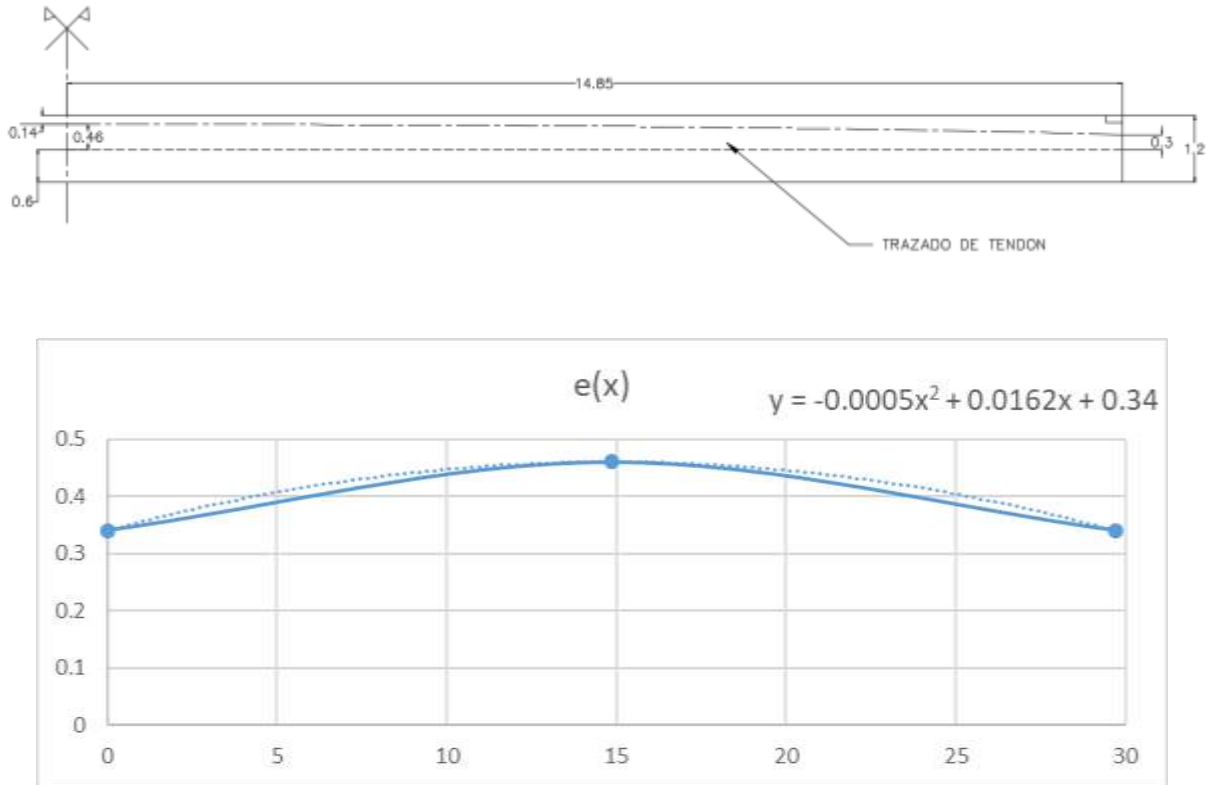
Concrete: HP-50/B/20/IIa

Active reinforcement: Y1860/S7  $f_{puk} = 1,860 \text{ N/mm}^2$   $f_{pyk} = 1,770 \text{ N/mm}^2$ ;  $\rho^\infty = 7 \%$ ;  $E_p = 190 \text{ GPa}$ ,  $\mu = 0.21$ ,  $k/\mu = 0.008\text{m}^{-1}$ , anchorage system:  $a = 5 \text{ mm}$

Passive reinforcement: B500 SD,  $f_{yk} = 500 \text{ N/mm}^2$ ;  $E_s = 200\text{GPa}$

### B) Design of the pre-stressed slab

- Pre-stressing force and the eccentricity required;
- Pre-stressing force at the mechanical anchorage, pre-stressing area, number of tendons, and diameter of the duct. Magnel diagram and solution in terms of “P” and “e”. Reflection and discussion. Layout of the active reinforcement in several sections and layout of the equivalent tendon;
- Short- and long-term stresses in 20 sections of the deck.



**Figure 12** Layout of the pre-stressing reinforcement.

Figure 12 shows the layout of the pre-stressing reinforcement, which was defined through an iterative procedure by trying to satisfy the conditions of the central kern along the whole length of the cantilever. The maximum eccentricity according to the durability specifications was adopted in the support section.

The pre-stressing force at the anchorage  $P_o$  should be lower than or equal to  $A_p \sigma_{po} = A_p \cdot \min \{0.75f_{p,max}; 0.85f_{pk}\}$ .

According to the exposure class IIa of EHE-08 (XC2 according to Eurocode-2, UNE-EN\_1992 § 4.2), the maximum crack width should be limited to 0.2 mm for the frequent combination, and the active reinforcement should be located in the compressed area of the section under the combination of quasi-permanent loads. The first condition will be accomplished directly if the tensile stresses in the concrete are limited to the concrete tensile strength,  $f_{ctm}$ .

To avoid the occurrence of compression cracks, for all persistent situations with the least favourable combination of actions, the compressive stresses in the concrete should satisfy  $\sigma_c \leq 0.60f_{ck}(t)$ , where  $f_{ck}(t)$  is the design characteristic strength at  $t$  days.

The least favourable section is the support section at the cantilever. Therefore, the pre-stressing force is design accomplishing cracking SLS at this section; in other words, Magnel conditions should be satisfied during transfer and in service in a long-term situation.

**Table 10** Material properties to be considered when designing the pre-stressing force

MATERIAL PROPERTIES			
CONCRETE		ACTIVE REINFORCEMENT	
$f_{ck}$ (MPa)	50	$f_{yp}$	1,770
$f_{cm, 28}$ (MPa)	58	$f_{up}$	1,860
$f_{ck, 7}$ (MPa)	35.2	$E_p$	190,000
$\sigma_{max, c}$ (MPa)	30	$\epsilon_{pyd}$	8.10E-03
$f_{ctm, IIa}$ (MPa)	$(f_{rec}: f_{ctm, 7} - p-p:0)$	$\epsilon_{pu}$	8.90E-03
$f_{ctm, 7}$ (MPa)	2.9	$\gamma_{p\_fav}$	0.9
$f_{ctm, 28}$ (MPa)	4.1	$\gamma_{p\_des}$	1.1
$E_c, 7$ (MPa)	27,808	$n_p, 7300$	5.57
$E_c, 28$ (MPa)	30,887	$F_{pmax}, A_p$ (kN)	
$E_c, 7300$ (MPa)	34,084	EC-2	EHE-08
$n_s, 28$	6.47	12,499.20	12,499.20
$n_p, 28$	6.15		

$$(1) \rightarrow \text{Transfer:}(f_{upper}) \rightarrow \frac{M_{pp}v}{I_c} + \frac{\gamma_p P_{ki} e_p' v}{I_c} + \frac{\gamma_p P_{ki}}{A_c} \leq \sigma_{max, c(7)} = 21.12 \text{ MPa}$$

$$\text{for } e_p' = 460 \text{ mm} \rightarrow P_{ki} < 9,770 \text{ kN}$$

$$(2) \rightarrow \text{Transfer:}(f_{lower}) \rightarrow \frac{M_{pp}v'}{I_c} + \frac{\gamma_p P_{ki} e_p' v'}{I_c} + \frac{\gamma_p P_{ki}}{A_c} \geq -f_{ctm, 7} = -2.9 \text{ MPa}$$

$$\text{for } e_p' = 460 \text{ mm} \rightarrow P_{ki} < 16,299 \text{ kN}$$

$$(3) \rightarrow \text{Service:}(f_{upper}) \rightarrow \frac{M_{frec}v}{I_c} + \frac{\gamma_p P_{\infty} e_p' v}{I_c} + \frac{\gamma_p P_{\infty}}{A_c} \geq -f_{ctm, 28} = -4.1 \text{ MPa}$$

$$\text{for } e_p' = 460 \text{ mm} \rightarrow P_{\infty} > 9,158 \text{ kN}$$

$$(4) \rightarrow \text{Service:}(f_{\text{lower}}) \rightarrow \frac{M_{p-p}V'}{I_c} + \frac{\gamma_p P_{\infty} e_p' V'}{I_c} + \frac{\gamma_p P_{\infty}}{A_c} \leq \sigma_{\text{max},c(28)} = 30 \text{ MPa}$$

$$\text{for } e_p' = 460 \text{ mm} \rightarrow P_{\infty} > -611 \text{ kN}$$

$$(5) \rightarrow \text{Service:}(f_{\text{pre-stressed tendon}}) \rightarrow \frac{M_{cp} e_p'}{I_c} + \frac{\gamma_p P_{\infty} e_p' e_p'}{I_c} + \frac{\gamma_p P_{\infty}}{A_c} \geq 0$$

$$\text{for } e_p' = 460 \text{ mm} \rightarrow P_{\infty} > 9,244 \text{ kN}$$

$$P_{\text{min,max}} = \{9,244 \text{ kN}, 9,770 \text{ kN}\}$$

Assuming 25% of pre-stressing losses,  $P_0 = 12,295 \text{ kN}$ , and dividing this value by the maximum stress value, the required pre-stressing area is  $8,813 \text{ mm}^2$ . Two tendons of 33 strands of 0.6" were chosen, the total pre-stressing area is equal to  $9,240 \text{ mm}^2$ , and a duct of 120 mm diameter has been assumed. Therefore, the maximum eccentricity allowed due to concrete cover requirements is equal to 0.46 m.

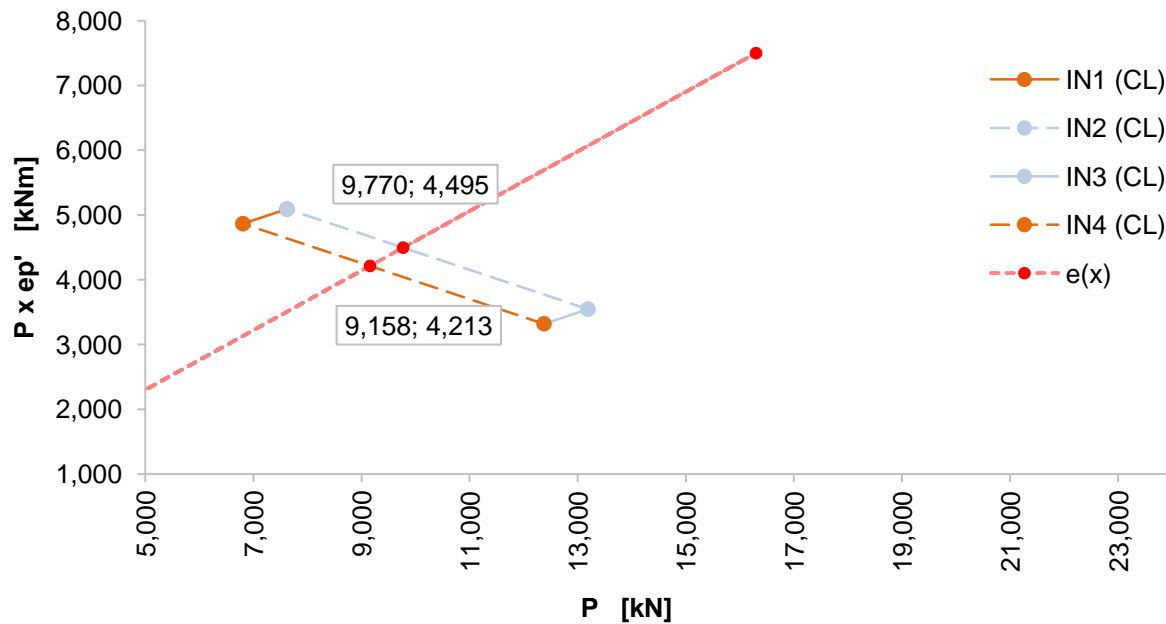


Figure 13 Magnel inequalities.

After defining the pre-stressing layout, the pre-stressing losses are calculated and then the concrete pre-stressed kern is calculated along the entire cantilever length. If the pre-stressing layout is inside the kern, and the active reinforcement is always pre-stressed for the quasi-permanent combination, the pre-stressing reinforcement design has been successfully accomplished. An iterative procedure should be applied in order to accomplish all the Magnel inequalities.

### Pre-stressing losses

#### 1) Instantaneous pre-stressing losses

##### a. Loss of force due to friction

$$\Delta P_1(x) = P_0(1 - e^{-(\mu\alpha(x) + kx)})$$

$$\mu \rightarrow 0.021$$

$$\alpha(x) \rightarrow e'^{(x)} - e'^{(x=0)}$$

$$\frac{K}{u} \rightarrow 0.008 \text{ m}^{-1}$$

$x \rightarrow$  Distance (m) between the studied section and the active anchorage

##### b. Loss due to wedge penetration

$$\Delta P_2(x) = \Delta P_{2,(x=0)} \frac{l_a - x}{l_a}$$

$$\Delta P_{2,(x=0)} = 2P_0(1 - e^{-(\mu\alpha(l_a) + kl_a)}) = 1,052.13 \text{ kN}$$

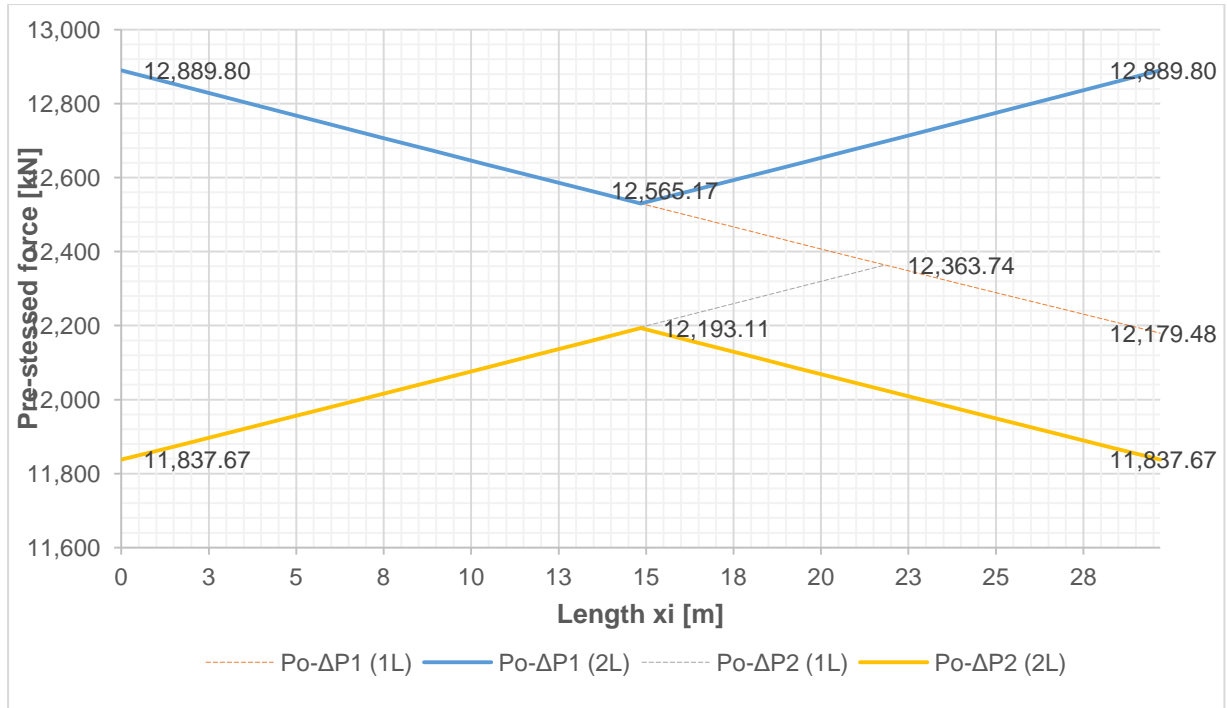
$$l_a = \frac{aE_p A_p}{\Delta P_1(l_a)} = \frac{aE_p A_p}{P_0(1 - e^{-(\mu\alpha(l_a) + kl_a)})} = 21.83 \text{ m}$$

##### c. Loss due to elastic shortening of concrete

$$\Delta P_3(x) = \frac{n-1}{2n} \sigma_{cp}(x) \frac{A_p E_p}{E_{c(7)}}$$

$$\sigma_{cp}(x) = \frac{\gamma_p(P_0 - \Delta P_1 - \Delta P_2)}{Ac} + \frac{\gamma_p(P_0 - \Delta P_1 - \Delta P_2)e_p'^2}{Ic} + \frac{(M_{pp}(x))e_p'}{Ic}$$

$$\Delta P_{ins}(x) = P_0 - \Delta P_1(x) - \Delta P_2(x) - \Delta P_3(x)$$



**Figure 14** Pre-stressing losses due to friction and wedge penetration when applying the tensile force in both free cantilever ends.

## 2) Deferred losses of pre-stressing

$$\Delta P_{dif}(x) = \frac{n\varphi(t, t_0)\sigma_{cp}(x) + E_p \varepsilon_{cs}(t, t_0) + 0.80 \Delta \sigma_{pr}(x)}{1 + n \frac{A_p}{A_c} \left( 1 + \frac{A_c y_p^2(x)}{I_c} \right) [1 + \chi \varphi(t, t_0)]} A_p$$

$$y_p(x) = e_p'(x) = 460 \text{ mm}; n_p = \frac{E_p}{E_c} = 5.57; \varphi(t, t_0) = \varphi_0 \beta_c(t, t_0) = 1.5036;$$

$$\varepsilon_{cs}(t, t_0) = \varepsilon_{cs(7300)} - \varepsilon_{cs(7)} = 2.83 \times 10^{-4}$$

$$\sigma_{cp}(x) = \frac{y_p P_{ki}(x)}{A_c} + \frac{y_p P_{ki}(x) e_p'^2}{I_c} + \frac{(M_{(PP+CM)}(x) e_p')}{I_c}; \Delta \sigma_{pr}(x) = \rho_f \frac{P_{ki}(x)}{A_p}; \rho_f = 7\%; \chi = 0.80$$

**Table 11** Pre-stressing force after instantaneous and deferred losses

x	e(x)	P <sub>ki</sub>	ΔP <sub>i</sub> (x)	%	P <sub>∞</sub>	ΔP <sub>dif</sub> (x)	%
0.00	0.34	11,459.12	1,431	11.10	9,300.56	3,589.24	27.85
1.49	0.36	11,474.05	1,416	10.98	9,377.70	3,512.10	27.25
2.97	0.38	11,495.73	1,394	10.82	9,365.48	3,524.32	27.34
4.46	0.40	11,525.28	1,365	10.59	9,388.68	3,501.12	27.16
5.94	0.42	11,563.57	1,326	10.29	9,450.94	3,438.86	26.68
7.43	0.43	11,611.23	1,279	9.92	9,554.83	3,334.97	25.87
8.91	0.44	11,668.63	1,221	9.47	9,701.79	3,188.01	24.73

x	e(x)	P <sub>ki</sub>	ΔP <sub>i</sub> (x)	%	P <sub>∞</sub>	ΔP <sub>dif</sub> (x)	%
10.40	0.45	11,735.91	1,154	8.95	9,892.22	2,997.58	23.26
11.88	0.46	11,812.95	1,077	8.35	10,125.42	2,764.38	21.45
13.37	0.46	11,899.39	990	7.68	10,399.63	2,490.17	19.32
14.85	0.46	11,994.62	895	6.94	10,712.00	2,177.80	16.90
16.34	0.46	11,899.39	990	7.68	10,399.63	2,490.17	19.32
17.82	0.46	11,812.95	1,077	8.35	10,125.42	2,764.38	21.45
19.31	0.45	11,735.91	1,154	8.95	9,892.22	2,997.58	23.26
20.79	0.44	11,668.63	1,221	9.47	9,701.79	3,188.01	24.73
22.28	0.43	11,611.23	1,279	9.92	9,554.83	3,334.97	25.87
23.76	0.42	11,563.57	1,326	10.29	9,450.94	3,438.86	26.68
25.25	0.40	11,525.28	1,365	10.59	9,388.68	3,501.12	27.16
26.73	0.38	11,495.73	1,394	10.82	9,365.48	3,524.32	27.34
28.22	0.36	11,474.05	1,416	10.98	9,377.70	3,512.10	27.25
29.70	0.34	11,459.12	1,431	11.10	9,300.56	3,589.24	27.85

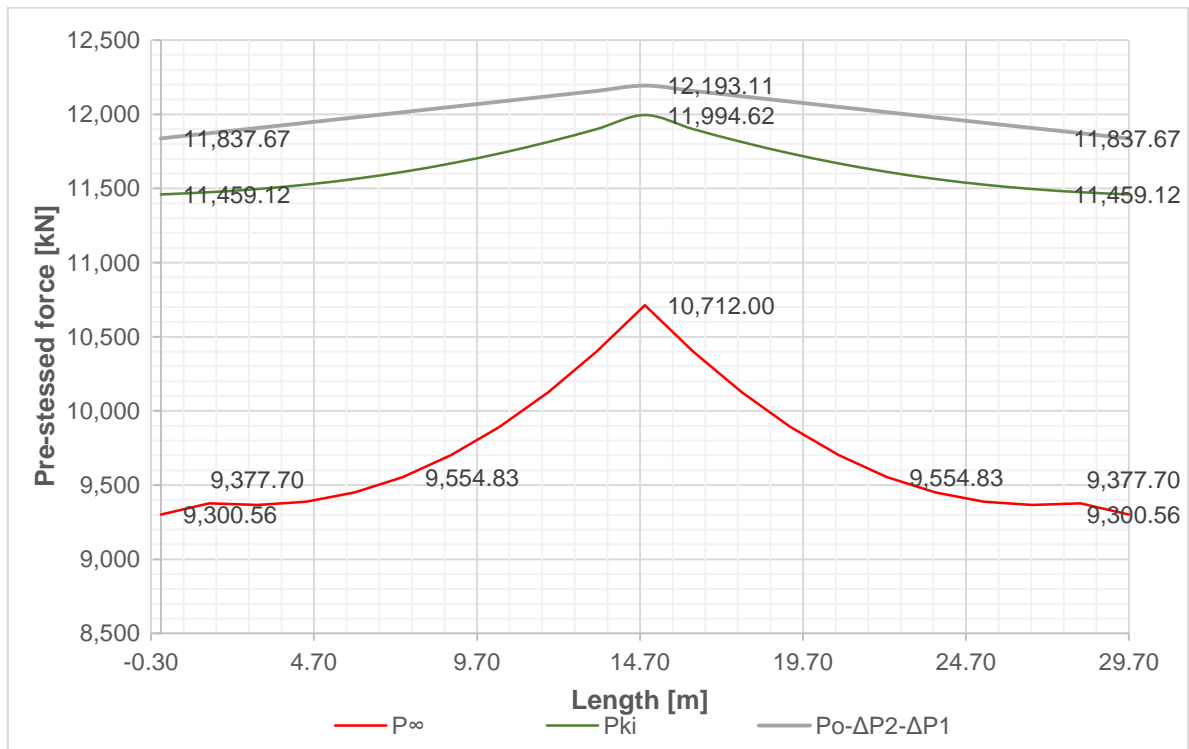
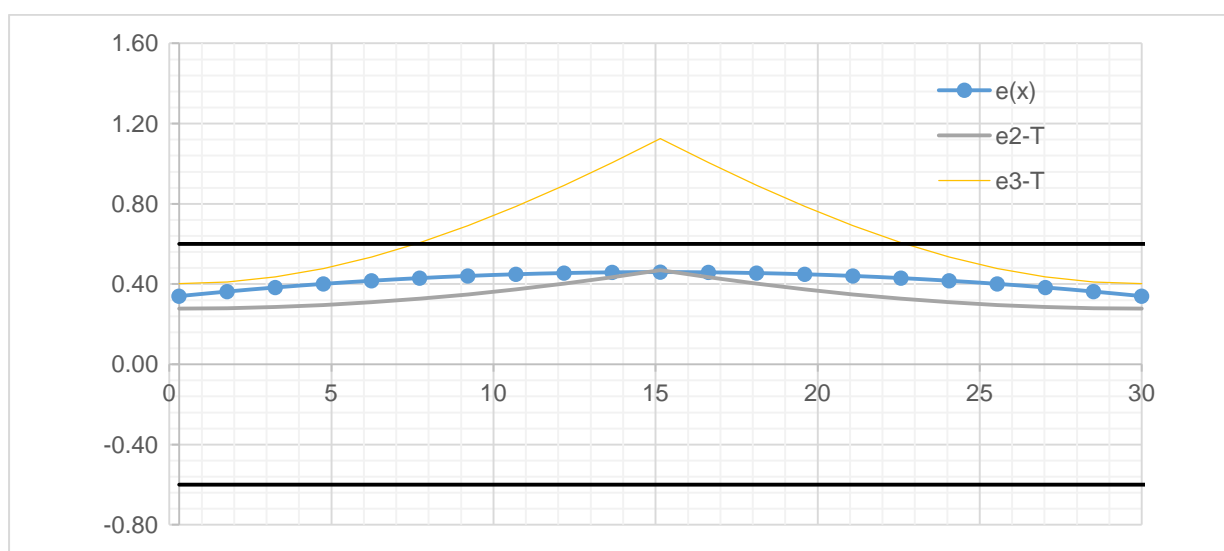
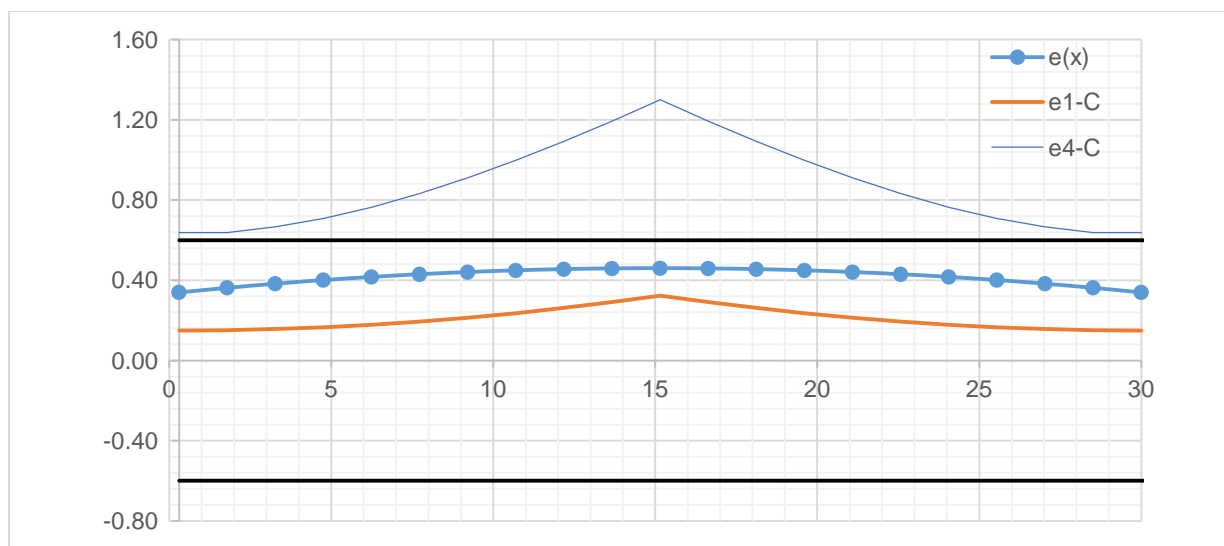


Figure 15 Pre-stressing force after instantaneous and deferred losses.

Finally, the central kern has been obtained along the length of the cantilever. As observed in Figure 16a, in which the section has been plotted together with the eccentricity and the compression central kern, the eccentricity is between both limits related to inequalities (1) and (4) Magnel. Therefore, both inequalities are directly met along the whole length of the studied slab. In addition, Figure 16b shows that the eccentricity fits in between the tensile central kern, accomplishing inequalities (2) and Magnel (3).



**Figure 16** a) Compression central kern; b) Tensile central kern.

**Table 12** Stress at the pre-stressing reinforcement for the quasi-permanent load-combination.

x	Ineq. (5) Magel	
0.00	15,537	ok
1.49	16,385	ok
2.97	16,690	ok
4.46	16,591	ok
5.94	16,056	ok
7.43	15,067	ok
8.91	13,612	ok
10.40	11,694	ok
11.88	9,321	ok
13.37	6,512	ok



x	Ineq. (5) Magel	
14.85	3,297	ok
16.34	6,512	ok
17.82	9,321	ok
19.31	11,694	ok
20.79	13,612	ok
22.28	15,067	ok
23.76	16,056	ok
25.25	16,591	ok
26.73	16,690	ok
28.22	16,385	ok
29.70	15,537	ok

- Cable elongation and vertical displacement due to the pre-stressing force at the free end of the cantilever. Long-term vertical displacement.

From the pre-stressing force after the friction losses, the cable elongation can be obtained as the integral of this profile along the cantilever length divided by the pre-stressing modulus of elasticity and the pre-stressing area.

$$\Delta l = \frac{P_0 - \Delta P_1(x=0) + P_0 - \Delta P_1(x=14.85)}{2A_p E_p} 14.85 = 0.108 \text{ m}$$

The total vertical deflection of the free end of the cantilever due to the pre-stressing force is the sum of the instantaneous and the long-term deflection.

$$\delta_{p,tot} = \delta_{p,inst} + \delta_{p,long-term}$$

$$\begin{aligned} \delta_{p,inst} &= \frac{\overline{P_{ki}} \sin \alpha L^3}{3E_{c,7} I_c} + \frac{\overline{P_{ki}} \cos \alpha \cdot e_p(x=0) \cdot L^2}{2E_{c,7} I_c} - \frac{\eta_p L^4}{8E_{c,7} I_c} = \\ &= \frac{188.39 \cdot 14.85^3}{3 \cdot 29,619,000 \cdot 0.153} + \frac{11678 \cdot 0.34 \cdot 14.85^2}{2 \cdot 29,619,000 \cdot 0.153} - \frac{12.68 \times 14.85^4}{8 \cdot 29,619,000 \cdot 0.153} = 0.125 \text{ m} \end{aligned}$$

$$\eta_p = P_{ki} e_p'' = 11,658 \cdot (-0.001088) = -12.68 \text{ kN/m}$$

$$\delta_{p,long-term} = \varphi(\infty, 7d) \delta_{p,inst} \frac{\overline{P_{ki}} + \overline{P_{\infty}}}{2 \cdot \overline{P_{ki}}} = 1.50 \cdot 0.125 \cdot \frac{11,680.0 + 9,806.9}{2 \cdot 11,680} = 0.172 \text{ m}$$

$$\delta_{p,tot} = \delta_{p,inst} + \delta_{p,long-term} = 0.125 + 0.172 = 0.297 \text{ m}$$

- Flexural ultimate limit state (ULS) in the worst section, arranging the necessary longitudinal passive reinforcements.

After verifying the SLS of cracking, the ULS of bending and shear should be checked in order to know if it is necessary to add passive reinforcement.

ULS bending with axial forces (pre-stressing force)

The compression block depth is first calculated to check if it is inside the flange; that is, if it is lower than 200 mm. If so, the ultimate bending moment can be calculated in a similar manner as that of a rectangular section.

$$y = \frac{A_p f_{pyd} d_p}{U_0} = 0.328 \text{ m} > 0.20 \text{ m} = h_f$$

where  $U_0 = f_{cd} b d_p = 45,933 \text{ kN}$ ,  $d_p = 1.06 \text{ m}$ ,  $A_p = 2 \cdot 33 \cdot 140 = 9,240 \text{ mm}^2$ ,  
 $f_{pyd} = f_{pyk} / \gamma_p = 1,770 / 1.15$

Therefore, the verification at ULS should be done assuming a T-section. The width of the section is assumed as the web thickness, and then the flanges are assumed as a fictitious compression reinforcement whose capacity is equal to:

$$U_{s0} = f_{cd} (b - b_w) h_f = \frac{50}{1.5} \cdot 0.8 \cdot 0.2 \cdot 1,000 = 5,333.33 \text{ kN}$$

$$U_0 = f_{cd} b_w d_p = 17,666 \text{ kN}$$

$$y = \frac{A_p f_{pyd} d_p}{U_0} - \frac{U_{s0}}{U_0} d_p = 0.8532 - \frac{5,333}{17,666} 1.06 = 0.533 \text{ m}$$

$$M_u = (A_p f_{pyd} - U_{s0}) (d_p - y/2) + U_{s0} (d_p - h_f/2) = (14,868 - 5,333.3) (1.06 - 0.533/2) + 5,333.3 \left( 1.06 - \frac{0.2}{2} \right) = 12,684 \text{ kN.m}$$

$$M_d(x = 14.85 \text{ m}) = 10,855 \text{ kN.m} \leq M_u = 12,684 \text{ kN.m}$$

The design bending moment at ULS combination in the least favourable section is lower than the ultimate value given by the cross-section area considering only the pre-stressing area.

- ULS of Shear, calculating the necessary transverse reinforcements

The least favourable section is the connection with the support where the design shear force, due to the external loads, is 1,461.98 kN. Since the slope of the pre-stressing layout at the support is zero, the shear pre-stressing component is also zero, and the reduced shear design force is 1,461.98 kN.

The design shear force should be lower than the ultimate shear limited by crushing of diagonal struts,  $V_{u1}$ , and lower than the ultimate shear force due to a tensile failure in the web,  $V_{u2}$ .

$$V_{u1} = K f_{1cd} b_0 d \frac{\cot\theta + \cot\alpha}{1 + \cot^2\theta} = 4,075.8 \text{ kN}$$

being

$$f_{1cd} = 20 \text{ MPa}; K = 1.25$$

since

$$\sigma'_{cd} = \frac{P_{\infty}(x=14.85)}{A_c} = 11.66 \leq 0.5 f_{cd}; b_0 = b_w - \eta \phi = 0.50 - 0.5 \cdot 2 \cdot 0.12 = 0.38 \text{ m}, \cot\theta = 1.9606, d = 1.06 \text{ m}$$

Assuming that the section is cracked at ULS:

$$\begin{aligned} V_{u2,woA90} &= \left[ \frac{0.18}{\gamma_c} \xi (100 f_{ck} \rho)^{1/3} + 0.15 \sigma'_{cd} \right] b_0 d = \\ &= [0.12 \cdot 1.43 \cdot (100 \cdot 50 \cdot 0.02)^{1/3} + 0.15 \cdot 11.66] 0.38 \cdot 1.06 = 1,025.32 \text{ kN} \end{aligned}$$

where

$$\xi = 1 + \sqrt{200/d} = 1.43 < 2; \rho = A_p / b_0 d = \frac{9,240}{380 \cdot 1,060} = 0.0229 < 0.02$$

$$V_{u2,minwoA90} = \left[ \frac{0.075}{\gamma_c} \xi^{3/2} f_{ck}^{1/2} + 0.15 \sigma'_{cd} \right] b_0 d = 949.1 \text{ kN}$$

since  $V_d \geq V_{u2,woA90}$ , passive transverse reinforcement is required:

$$V_{u2,wA90} = V_{cu} + V_{su}$$

$$V_{cu} = \left[ \frac{0.15}{\gamma_c} \xi (100 f_{ck} \rho)^{1/3} + 0.15 \sigma'_{cd} \right] b_0 d =$$

$$= [0.10 \cdot 1.43 \cdot (100 \cdot 50 \cdot 0.02)^{1/3} + 0.15 \cdot 11.66] 0.38 \cdot 1.06 = 971.85 \text{ kN}$$

$$V_{su} \geq V_d - V_{cu} = 1,461.98 - 971.85 = 490.12 \text{ kN}$$

$$V_{su} = z \sin \alpha (\cot \alpha + \cot \theta) A_{90} f_{y90d}$$

$$A_{90} = \frac{V_{su}}{z \sin \alpha (\cot \alpha + \cot \theta) f_{y90d}} = 0.655 \text{ mm}$$

where  $z = 0.9 \cdot d = 0.954 \text{ m}$

The transverse reinforcement will be two closed stirrups  $\phi 12/0.30$  ( $2.753 \text{ mm}^2/\text{mm}$ )

- Anchorage devices, checking the stresses in the concrete under them, and defining the required passive reinforcement

According to the MK4 catalogue, the dimensions of the anchor plates are  $444 \text{ mm} \times 444 \text{ mm}$ . The layout in plan view should be modified to be able to implement the anchor plates, leaving a free space between them of  $100 \text{ mm}$ . Therefore, the spacing between the two tendons of each web should be  $554 \text{ mm}$  at the anchor area and  $240 \text{ mm}$  at the support connection.

- Drawings of the overall solution geometry and drawings of the passive and active reinforcements.

The proposed solution can be consulted in detail in *Annex XIV*.

### C) Obtain the bill of quantities of the design project

As an example, the bill of quantities is provided for the slab and the concrete wall, considering only concrete, active and passive reinforcement, and the formwork; the final sum is  $195,366.16 \text{ €}$ . Detailed calculations can be found in *Annex XV*.

BILL OF QUANTITIES							
m³	Concrete for pre-stressed elements with a maximum aggregate size of 20 mm						104.87 €
	Description	A	B	C	D	Quantity	Amount
	Deck	25.8	33.38	0.70769		609.47	63,914.85 €
	Intermediate Wall	1	25.8	1	6	154.80	16,233.88 €
Total quantity						764.27	80,148.73 €
kg	Internal steel reinforcement B500S in the form of corrugated rebars with a yield strength ≥ 500 N/mm2						1.16 €
	Description	A	B	C	D	Quantity	Amount
	Deck	21.84	25.8	33.38		563.34	653.48 €
	Intermediate Wall	40.44	25.8	6		6260.12	7,261.74 €
Total quantity						6,823.47	7,915.22 €
kg	Tendon made of strands for active reinforcement Y 1860 S7, till 37 strands of 15.2 mm of nominal diameter in ducts of less than 70 m length						1.39 €
	Description	A	B	C	D	Quantity	Amount
	Deck	25.8	50.77	33.38	1.099	48,051.21	66,791.18 €
				Total quantity		48,051.21	66,791.18 €
m²	Assembly and disassembly of formwork with pine wood board for exposed concrete						34.25 €
	Description	A	B	C	D	Quantity	Amount
	Deck	25.8	33.38			861.204	29,496.24 €
		2	25.8			51.6	1,767.30 €
		2	33.38			66.76	2,286.53 €
	Wall	1	1	6	2	12	411.00 €
		1	25.8	6	2	309.6	10,603.80 €
				Total quantity		1,182.804	40,511.04 €
TOTAL AMOUNT							195,366.16 €

### Evaluation criteria

In order to evaluate this activity, a report will be requested from each group, in which the entire activity should be solved. The report should include index construction and justification and all calculations and schematic drawings associated to the solution proposed.

For the specific assessment of the report, we recommend using the rubric mentioned previously (see *Annex IX*), and specifically, the technical aspects identified within the rubric. Thus, the rubric represents a possible instrument to facilitate the evaluation of the proposed activities as a whole. As mentioned above, the professor is free to choose an alternative method.

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## ANNEXES

- I. Vall d'Hebron neighborhood data < A.I\_Vall\_Hebron.pdf >
- II. Horta neighborhood data < A.II\_Horta.pdf >
- III. La Guineueta neighborhood data < A.III\_Guineueta.pdf >
- IV. Canyelles neighborhood data < A.IV\_Canyelles.pdf >
- V. Les Roquetes neighborhood data < A.V\_Roquetes.pdf >
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- VIII. La Trinitat Nova neighborhood data < A.VIII\_Trinitat\_Nova.pdf >
- IX. Evaluation rubric < A.IX\_Evaluation\_rubric.pdf >
- X. Course schedule example < A.X\_Course\_schedule.pdf >
- XI. Code of ethics example < A.XI\_Ethics\_code\_ASCE.pdf >
- XII. Barcelona city topography < A.XII\_Topography.dwg >
- XIII. Detailed calculations < A.XIII\_Calculus.xlsx >
- XIV. Proposed graphical solution < A.XIV\_Graphical\_solution.dwg >
- XV. Bill of quantities < A.XV\_Bill\_quantities.xlsx >



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# Dimensioning a Drinking Water Distribution Network in Collique (Lima): Introduction to the Human Right to Water and Sanitation

Helena Grau Huguet and Emeka Okpala



PHOTO: "Illegal right". Lima. Miren Etxeberria



# CASE STUDIES **Dimensioning a Drinking Water Distribution Network in Collique (Lima): Introduction to the Human Right to Water and Sanitation**

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# 5

## DIMENSIONING A DRINKING WATER DISTRIBUTION NETWORK IN COLLIQUE (LIMA): INTRODUCTION TO THE HUMAN RIGHT TO WATER AND SANITATION

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## 1. INTRODUCTION

In 2010, the UN General Assembly and the UN Human Rights Council recognized water and sanitation as a Human Right (HR). Undoubtedly, this milestone represents a great advance in the water, sanitation, and hygiene sector (WaSH) as it gives all humans the right to the provision of minimum standards in relation to these services (Flores-Baquero, 2015).

The 2030 Agenda for Sustainable Development, adopted by the UN General Assembly in 2015, integrates a specific objective for water and sanitation (SDG 6). This Objective pursues the ambitious goal of "ensuring the availability of water and its sustainable management and sanitation for all". Clearly, SDG 6 reflects the human right to water and sanitation (HRtWS). However, there are still many millions of people who do not enjoy their fundamental rights of access to drinking water and sanitation. Many of them face significant barriers to access because of where they live and who they are. Water and sanitation for all will not be achieved without paying special attention to the needs of vulnerable and marginalized groups.

For HRtWS realization, it was proposed to define and act over 5 dimensions; availability, accessibility (physical), quality, affordability, and acceptability. In this case study, we will focus on drinking water access from a Human Right approach. In this sense, we will briefly introduce the current situation regarding access to this service, and we will go in more depth into the meaning of the HRtWS dimensions, and specifically, in the case of drinking water. Secondly, we will introduce the situation of access to this service in a peri-urban area of the metropolitan city of Lima. Finally, we will synthetically present a research work carried out with the inhabitants of this area in relation to HRtWS. Altogether, this will make up the work context in which the students will carry out the proposed activities

### 1.1. DISCIPLINES COVERED

The distribution of a drinking water service is usually found in the field of civil engineering, and usually in subjects of urban planning, urban services, or hydraulics. With this case study, we aim to put into practice different theoretical knowledge for the calculation and pre-dimensioning of drinking water supply networks.

In addition, the background that it will provide in regard to non-conventional water distribution approaches will help future professionals, who are willing to dedicate themselves to basic services management, to gain a broader perspective.

## 1.2. LEARNING OUTCOMES

As a result of this case study, students are expected to be able to:

- Pre-dimension a water supply network based on public fountains for an unconventional urban sector;
- Analyze the impacts associated with the Human Right to Water (HRtW) compliance;
- Understand the different methods of the drinking water supply, as well as the management and associated payment processes for it;
- Analyze the impact associated with these management aspects.

## 1.3. ACTIVITIES

This case of study is based on two activities. A first class activity is subdivided into two blocks. The first block will be invite to reflect on the importance of access to water services. This reflection will be carried out from a Human Right perspective. The second block, in the form of a "guided workshop", aims to provide the basic knowledge on the dimensions of a water distribution network.

The second activity will be carried out autonomously, but in small groups (of 3 to 4 people). The purpose of this activity is for the students to apply the knowledge they acquired in the classroom to consider a larger water supply network. Likewise, it will be urged that they extend their previous reflections on the managerial aspects of this service.

## 2. DESCRIPTION OF THE CONTEXT

In this section, we introduce the basic concepts associated with the Sustainable Development Goals (SDGs) and their monitoring, as well as the different dimensions of the HRtWS. Next, we provide detailed information of the context that this case study addresses. Specifically, we present data associated with water management approaches and the perception of a number of inhabitants as far as the relative importance of HRtW dimensions. Finally, we introduce a possible way of quantifying / evaluating this information.



## 2.1. WATER, SANITATION, AND HYGIENE GLOBAL CONTEXT

In 2015, the United Nations General Assembly adopted the 2030 Agenda for Sustainable Development, a plan of action in favor of people, the planet, and prosperity, which also intends to strengthen universal peace and access to justice. This agenda establishes 17 SDGs and 169 goals designed to be universally relevant and applicable to all countries. The SDGs require an integrated approach with respect to social, economic, and environmental dimensions. As for the Millennium Development Goals (MDGs) formulated for the period between 2000 and 2015, the SDGs integrate a specific objective for water and sanitation (SDG 6).

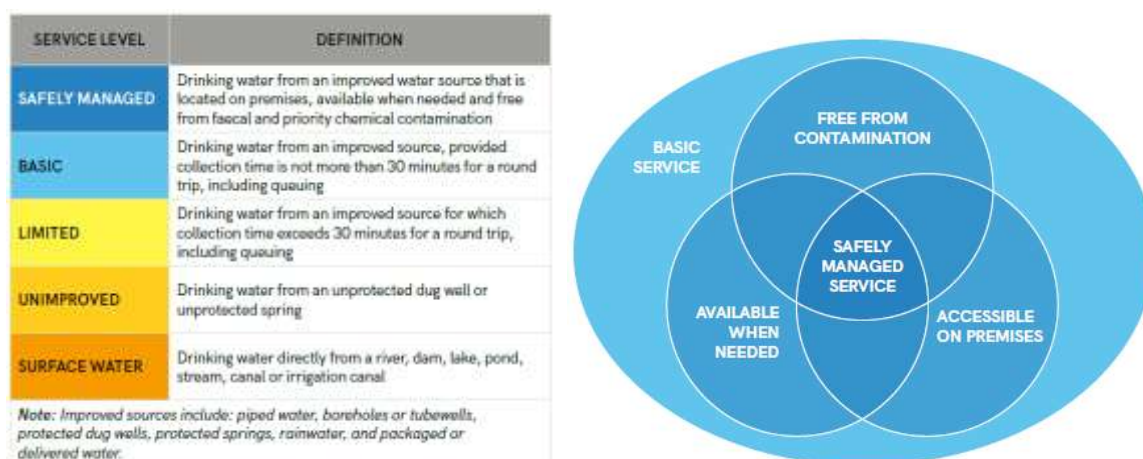
This deserved prominence is based on the recognition of access to water, sanitation, and hygiene (WaSH) as fundamental aspects for human development and well-being (Carter et al., 1999; Cairncross & Valdmanis, 2006). Additionally, the improvement of these aspects in households, health centers, schools, and workplaces, complemented with the treatment of wastewater, is a way to reduce the risk of waterborne diseases, to achieve adequate nutrition, to support education and work, and to address overarching issues, such as poverty eradication and gender inequality and other inequalities (Joint Monitoring Program, 2015, UN-Water, 2016).

What SDG 6 proposes is "to guarantee the availability of water and its sustainable management and sanitation for all". With this in mind, eight specific targets have been formulated, six of which are based on expected outcomes and the remaining two, based on the means of implementing these outcomes. *Table 1* briefly details the proposed targets.

**Table 1** *Specific targets integrated in SDG 6.*

TARGET	DESCRIPTION
6.1	Achieve universal and equitable access to safe drinking water at an affordable price for all
6.2	Achieve access to adequate and equitable sanitation and hygiene services for all
6.3	Improve water quality and reduce pollution
6.4	Increase the efficient use of water resources
6.5	Implement Integrated Water Resource Management (IWRM)
6.6	Protect and restore water-related ecosystems
6.a	Expand international cooperation
6.b	Support and strengthen local community participation

In this context, monitoring and evaluation have been fundamental for sound decision-making, since governments, civil society, and donors need objective and reliable data on which to base planning, prioritization, and accountability mechanisms. In this regard, the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) combined efforts in 1990 with the Joint Monitoring Program (JMP) for Water Supply and Sanitation, whose main objective was and is to monitor national progress towards the universality of access to safe water and sanitation. Since then, the water and sanitation sector has undergone an important transition in the way it evaluates access to these services. Initially, basically only indicators quantifying the mere access to water or sanitation infrastructure (in terms of coverage) were used. Progressively, sector monitoring was carried out in broader terms of "level or quality of service". Currently, the JMP proposes three "ladders" to monitor the specific targets 6.1 and 6.2. In *Figure 1*, the indicators proposed for access to water are presented, as this service will be the main focus of this case study.



**Figure 1** The new JMP ladder for drinking water services. Source: Joint Monitoring Programme, 2017.

The global situation in 2015, as reflected in JMP (2017), reflects that 71% of the world population (5.2 billion people) use a safely managed drinking water service, i.e., one that is located on premises, available when needed, and free from contamination (*Figure 1*). In relation to this figure, one in three people live in rural areas. On the other hand, 89% of the world population (6.5 billion people) uses at least a basic service, i.e., an improved water source with a location that requires a maximum of 30 minutes to make a round trip to collect water (including queuing). The most worrisome figures, which represent the important challenge facing the sector, show that 844 million people lacked a basic drinking water service in 2015, with 263 million people spending more than 30 minutes per round trip to fetch water from an improved source (which constitutes a limited drinking water service), and that 159 million people still collected water for consumption directly from surface water sources (58% of whom live in sub-Saharan Africa).

## 2.2. HUMAN RIGHT TO WATER AND SANITATION

Human rights are universal, inalienable, interdependent, and interrelated. The Universal Declaration of Human Rights stipulates that "all human beings are born free and equal in dignity and rights". Having access to drinking water and sanitation is fundamental for living a dignified life and defending Human Rights (United Nations and World Health Organization, 2012).

The recognition of the HRtWS by the resolutions of the General Assembly and the United Nations Human Rights Council in 2010 (United Nations General Assembly, 2010a; 2010b) represents a great advance in the WaSH sector, as it grants all human beings the right to the provision of minimum standards in relation to these services (Flores-Baquero, 2015). Undoubtedly, SDG 6 reflects the impregnation of the recognition of water and sanitation as a human right.

Thus, HRtWS has been interpreted as the right of everyone to have access to a water (and sanitation) service that is sufficient, safe, accessible, culturally acceptable, and affordable for personal and domestic use, and that must be provided in a participatory manner that is responsible and non-discriminatory (Flores-Baquero, 2015). In this sense, and for the realization of this human right, five dimensions were proposed: availability, (physical) accessibility, quality, affordability, and acceptability. Flores-Baquero (2015) makes a descriptive synthesis that is detailed below.

### **“Availability**

The water supply for each person must be sufficient and continuous for personal and domestic uses. These uses ordinarily include drinking, personal sanitation, washing of clothes, food preparation, personal and household hygiene. The quantity of water available for each person should correspond to World Health Organization (WHO) guidelines. Neither continuity nor exact quantity required can be determined in the abstract, since individual requirements for water consumption vary, for instance due to climatic conditions, level of physical activity and personal health conditions.

### **Accessibility**

Water facilities must be physically accessible for everyone within, or in the immediate vicinity of, each household, health or educational institution, public institutions and places, and the workplace. Even where water facilities exist, they are frequently inaccessible for different reasons. Around the world, water points are often a long distance from the home, so people, especially girls and women, spend major portions of their day walking to collect water for their daily needs. The distance to the water source should be in reach

of every household, bearing in mind the special needs of certain groups and individuals; a high source:person ratio is often a reason that undermines physical accessibility; People's security is often threatened on their way to or while using the service. The path leading to the facility or water source itself, should be safe and convenient for all users, including children, older people, persons with disabilities, women, including pregnant women, and chronically ill people; the facility itself should be accessible for all users and easy to use.

### **Quality**

Water must be of such a quality that it does not pose a threat to human health. The transmission of water-borne diseases via contaminated water must be avoided. In its *Guidelines for Drinking-water Quality*, WHO defines safe drinking water as water that “does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages”. The maximum limits provided in the *Guidelines* for a wide range of potentially harmful substances can serve as a reference point.

### **Affordability**

Water facilities and services must be available for use at a price that is affordable to all people. The provision of services includes construction, maintenance of facilities and treatment of water. Paying for these services must not limit people's capacity to acquire other basic goods and services guaranteed by human rights, such as food, housing, health services and education. Affordability does not necessarily require services to be provided free of charge. Special caution must be exercised and due process guaranteed in cases of disconnection from the water supply due to a user's inability to pay. Measures must be in place to ensure that such users are not deprived of access to safe water to meet their most basic personal and domestic needs.

### **Acceptability**

Perspectives differ with regard to which water supply solutions are acceptable in a given context. Acceptability is relevant for encouraging people to use safe water sources. In particular, water should be of an acceptable color, odor and taste. The placement of a water point or the actual water source should also be acceptable to them. Cultural prescriptions may also apply to conditions for use of these facilities.”

As stated above, there are still billions of people who do not enjoy their fundamental rights of access to safe drinking water (and sanitation). Many of them face significant barriers to access due to where they live and who they are. Are they women? Do they belong to an ethnic minority? Are they poor? Do they live in a slum or in an impoverished rural area?

Governments have an obligation to ensure access to water and sanitation for all members of the population, regardless of whether they are rich or poor, male or female, living in formal or informal settlements, or in urban or in remote rural areas (United Nations and World Health Organization, 2012).

Water and sanitation for all will not be achieved unless we pay particular attention to the needs of vulnerable and marginalized groups. Human right principles highlight the need to actively design water and sanitation policies that prioritize and address the needs of vulnerable and marginalized groups, rather than treating all persons as if they faced identical challenges in accessing safe water and improved sanitation. Water and sanitation for vulnerable and marginalized groups is often a social exclusion issue, and not just a water issue (United Nations and World Health Organization, 2012).

### 2.3. CASE STUDY: COLLIQUE (LIMA, PERU)

Peru is divided into three macro regions called Costa, Sierra, and Selva. The first of these regions is a desert area in which most of the population lives (INEI, 2015). Strikingly, it is the hydrographic area that possesses only 2.2% of the total fresh water available in the country (ANA, 2016). According to the report presented by the JMP (2017), 95% of the urban population has access to a basic service (see the JMP ladder), while the percentage corresponding to the rural population is reduced to 72%. In this regard, it should be noted that there are no estimations regarding safely managed access or estimations associated with peri-urban areas.

The Peruvian capital, Lima, is the second largest city in the world (after Cairo) that is located on top of a desert. Its territory is formed by “cerros” (mountains of low altitude), and river degradation and aquifer overexploitation reinforce the scarcity of the resource (Ioris, 2016). The Lima Metropolitan comprises 30% of the country’s population, with 9,904,000 inhabitants (INEI, 2015), although the exact numbers are difficult to specify due to the high number of informal neighborhoods (known as human settlements) located in the periphery of the city. Regarding the central theme of this case study, the figures recorded show a drinking water coverage of 92.7%, whereby 83% of the connections have a water meter, and a sanitation coverage of 89.4% (SUNASS, 2015).

The high population growth of 1.8% per year (Municipalidad Metropolitana de Lima, 2016) is especially due to the migration of people with fewer resources, which generates additional pressure in areas of Lima that lack adequate supplies of water and sanitation as well as electricity (see *Table 2*).

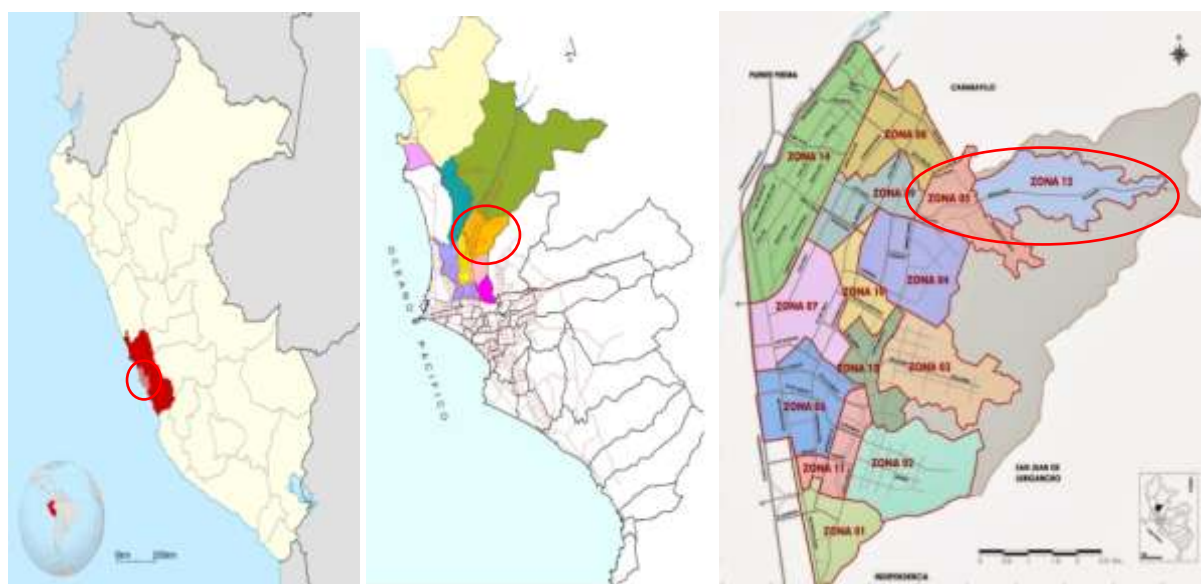
**Table 2** Socio-spatial inequalities in the municipalities of Metropolitan Lima in terms of water access.

Source: Ioris, 2016.

ECONOMIC CONDITION	NUMBER OF HOUSEHOLDS	HOUSEHOLD PERCENTAGE WITH WATER SERVICE
High-income municipalities	92,276	99.8
Medium-income municipalities	184,187	77.9
Low-income municipalities	712,878	68.1

## Collique

The neighborhood of Collique is part of the Comas district (fourth largest population district of Lima), located in the northeast of it.



**Figure 2** Geographic location of the study area. Source: Own elaboration.

Collique comprises 8 zones and has approximately 116,000 inhabitants, although this figure is difficult to know exactly due to the problems with the census in the most peri-urban areas of the metropolis. The size of the neighborhood is approximately 5 km<sup>2</sup>, and population density reaches more than 23,200 inhab/km<sup>2</sup>. For comparison, Table 3 presents the figures for the city of Lima, the district of Comas, and the neighborhood of Collique.



**Table 3** Comparison among locations of population, area, and density

	INHABITANTS	AREA (km <sup>2</sup> )	POPULATION DENSITY (inhab/km <sup>2</sup> )
Lima	7,605,742	2,670	2,854
Comas	525,000	48,72	11,000
Collique	116,000	5	23,200

The urban planning of Collique is developed from the “Avenida Revolución” (*Figure 3*). This avenue runs through the lower part of the valley, where the neighborhood is located, and is the starting point for the rest of the urban roads that leave for the “cerros”. The avenue is the central axis of Collique in all aspects—most of the facilities are grouped around it; it connects the neighborhood with the rest of the district in terms of mobility; and it is the axis of the urban services (among them, drinking water and sanitation).



**Figure 3** Distribution of Collique neighborhood around Avenida Revolución. Source: Own elaboration, from Google Maps.

It must be borne in mind that as the distance from a residence to the central avenue, access to urban services decreases. Building processes in Collique have taken place faster than the urbanization processes, which has produced a late supply of services to many areas that have already been built. This urbanization was made *a posteriori* thanks to citizen protests. The division of the neighborhood into eight different areas with some autonomy resulted in unequal access to services. The central Lima administration proposed a co-payment to these peri-urban areas for the provision of water and sanitation services, while many of the neighborhoods demanded the services to be 100% funded with public funds. Those districts that accepted the co-payment had a faster access to the services.

Another noteworthy aspect is the expansion of the neighborhoods that has been carried out in the “cerros”. Normally, the land for houses is built by dynamiting areas of the mountain to break the rock and to produce as flat a surface as possible. In many cases, house foundations are built with the dynamited stone. In these sectors, streets are either inexistent or are minimal and very thin, which limits physical access to all homes (*Figure 4*). In short, this unequal growth of the neighborhood produced the low homogeneity of the supply system in Collique.



**Figure 4** Household distribution of homes in the neighborhood of Collique. Source: Own elaboration.

## 2.4. WATER MANAGEMENT IN COLLIQUE

Drinking water distribution networks, as well as their management, are fundamental for guaranteeing a correct level of service to the population. Drinking water infrastructure and service in Lima are mainly the responsibility of the public company SEDAPAL (Servicio de Agua Potable y Alcantarillado de Lima; “Lima Potable Water and Sewage Service”). However, in Collique, it is possible to find four different forms of supply, which are presented below.

### Community “Pilón”

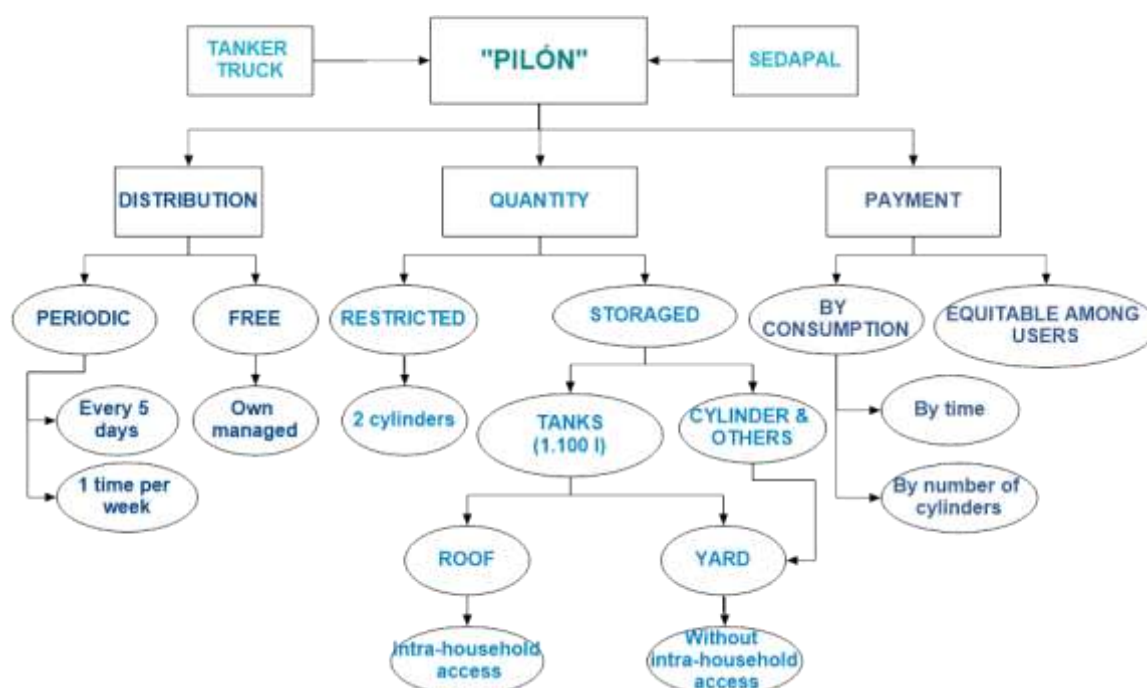
The community “pilón” (community fountain) is one of the most common forms of supply in the area of the “cerros”, where human settlements are located. These systems have been built and financed by NGOs, which have trained the population in their organization and proper functioning and management of the system (creation of the “pilón” committee).

The operation of the “pilón” consists of storing the water in a tank, which can be supplied by SEDAPAL network or by tanker trucks (see *Figure 5*). These trucks distribute the water through pipes to each “pilón” (access points to water), generally distributed by block, and for which a hose is connected to bring the water point closer to the storage places of the households. Water distribution can be periodic (every “x” days), or unrestricted, which



means that there should be the possibility of being supplied when needed. The water amount, when it is not restricted, depends on the storage capacity of each household; when the storage tanks are located on the roof, it favors the possibility of having an intra-household connection.

The price of the service is determined by the type of supply of the distributor tank. Provision by tanker trucks is more expensive than provision by SEDAPAL, since it is a private service. The payment system depends on each committee organization and this can either be equitable among users (i.e., the total price is divided by the number of users) or by quantity consumed.



**Figure 5** Community “pilon” distribution scheme in Collique. Source: Own elaboration.

Because it is a community system, its management through a committee is a determining factor for ensuring a good level of service for all users. It has been observed that most of the committees charge a price over the water cost in order to generate some funds for the maintenance of the facilities or for paying electricity when pumps are required. For example, in the seventh zone of Collique, the tanker truck sells the “tank” for 130 soles<sup>1</sup> (12 m<sup>3</sup>, which equals 60 cylinders), so that the price of a single cylinder is about 2.16 soles; however, the committee charges 2.30 per cylinder to pay the electricity bill for the pump and maintenance of the system. In contrast, in the eighth zone, where the “pilones” are supplied by SEDAPAL,

<sup>1</sup> The Sol is the currency of Peru since 1991. Initially called Nuevo Sol (S /.), since 2015, the government ordered that this currency be simply called “Sol (S /.)”, also suppressing the use of the dot (S /.) in the monetary sign. 1 S / equals 0.25 euros (€) and 0.31 US dollars (US \$).

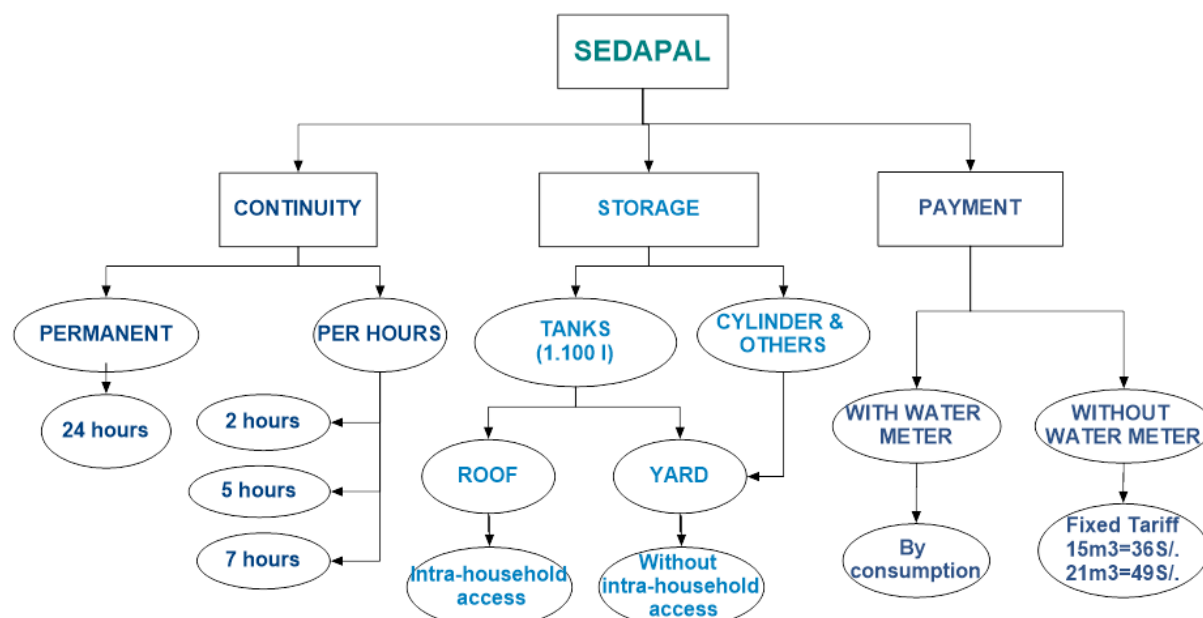
the price is 0.5 soles per cylinder. This was initially the end price for the users until the committee, together with the users, decided to increase the price to 1 sol to raise funds for maintenance. Some—but not all—committees are transparent with respect to their accounts, sharing with their users the state of funds and what they are used for.

## SEDAPAL

The most widespread form of water supply in Collique is the connection to SEDAPAL network, with the largest number of connected users located near the main avenue. As shown in *Figure 6*, having a connection to the network is not a guarantee for a 24-hour permanent service, as there are areas where the availability is only two hours per day and at different times.

The amount of water available depends on the storage capacity of each household and the pressure of the network. Likewise, for community “pilón” systems, intradomiciliary access depends on the infrastructure (e.g., tank on the roof, and pump in case of little pressure) and therefore on the economic resources of each residence.

This supply form is the most economical as long as water consumption is metered (payment for consumption). Otherwise, the price can be harmful if the consumption is low and charged at a fixed rate (e.g., constant price regardless consumption), or beneficial if the actual consumption is greater than the invoiced consumption (as observed for large families).



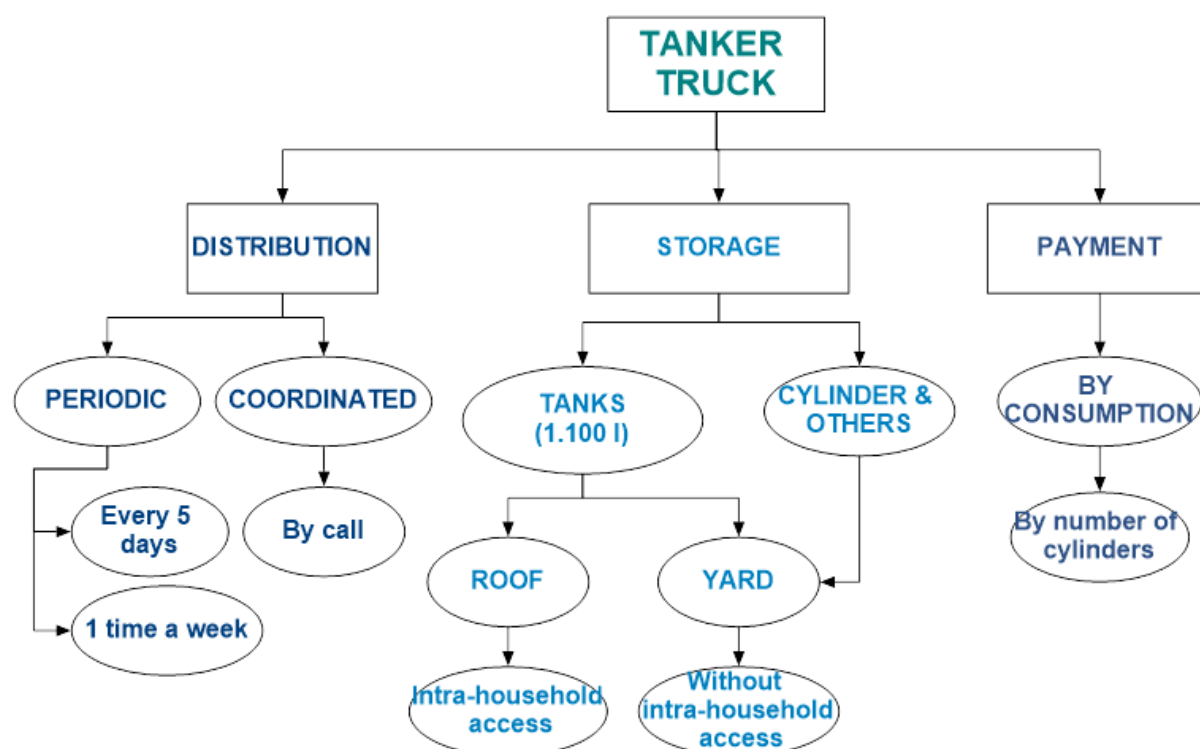
**Figure 6** SEDAPAL distribution scheme in Collique. Source: Own elaboration.

As an example, in the first zone, which has a fixed rate due to the lack of a water meter, users pay 49 soles for 21 m<sup>3</sup> and have 7 hours of daily water service. In contrast, in the fifth zone, where users likewise do not have a water meter, users pay a fixed fee of 36 soles for 15m<sup>3</sup> and 2 hours of daily service.

## Tanker truck

Supply by tanker truck that been reduced in Collique due to an increased coverage of SEDAPAL network and to alternative forms of supply, such as the “pilón”.

Tanker trucks transport the water collected from SEDAPAL dispensers, which guarantee the "quality" of the water, or from clandestine dispensers, which do not clarify water origin or quality. This service is usually from individuals in the water distribution business, in a coordinated or periodic way (see *Figure 7*), to places where there are no other forms of supply. These trucks mainly supply storage tanks for the “pilonés”, charging for the "tank" from 120 soles (in the fifth zone) to 160 soles (in the eighth zone). The cost of water directly sold to individuals is more expensive due to the fact that water distribution requires more time, reaching 4.20 soles per cylinder (200 liters), which means a price that is more than 16 times higher than the price of SEDAPAL.



**Figure 7** Tanker trucks distribution scheme in Collique. Source: Own elaboration.

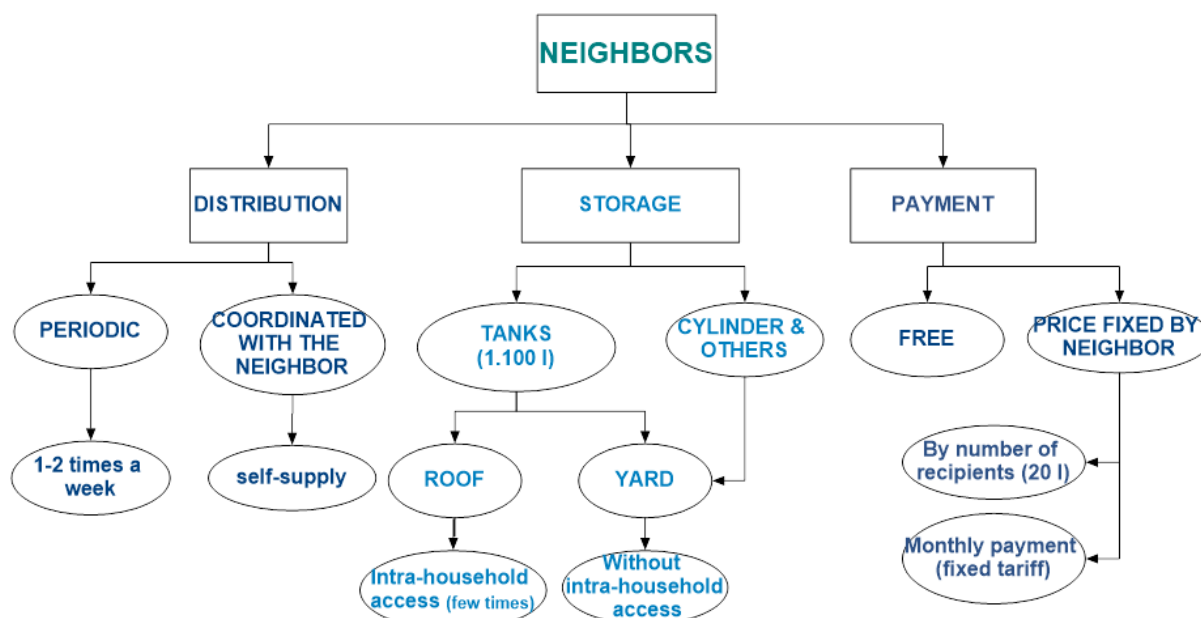
## Community members (neighbors)

This is a supply form that arises from necessity when water access from the other forms presented above is impossible. The main reason for sourcing from neighbors is the lack of a communication channel that reaches households without service, either due to the slope of the land, the high density of households, or the impossibility of truck access through a road.

Several cases have been observed in which there was a community “pilón” near these households without water. In such situations, neighbors usually negotiate with the “pilón” committee in order to be allowed access to water. However, they are required to pay the fee and to install the necessary pump and hose to supply water to their homes. If this does not happen, neighbors ask water users (usually those connected to the network) to provide them with water or to sell it to them.

In Collique, where most households that are connected to the network pay a fixed fee, giving water away does not represent any expense. Nevertheless, there are cases neighbors who do business by selling water for which they do not pay.

Water storage is similar to previous cases (“pilón”, SEDAPAL, or tanker truck), with the same advantages and disadvantages depending on where the water is stored. However, in this case, because water is not available, households usually do not have intrahousehold facilities. The price of this “service” is the most expensive form of water supply.



**Figure 8** Distribution scheme through the neighbors in Collique. Source: Own elaboration.

## Summary

To facilitate a comparison between the management systems presented, *Table 4* summarizes some of the most noteworthy aspects.

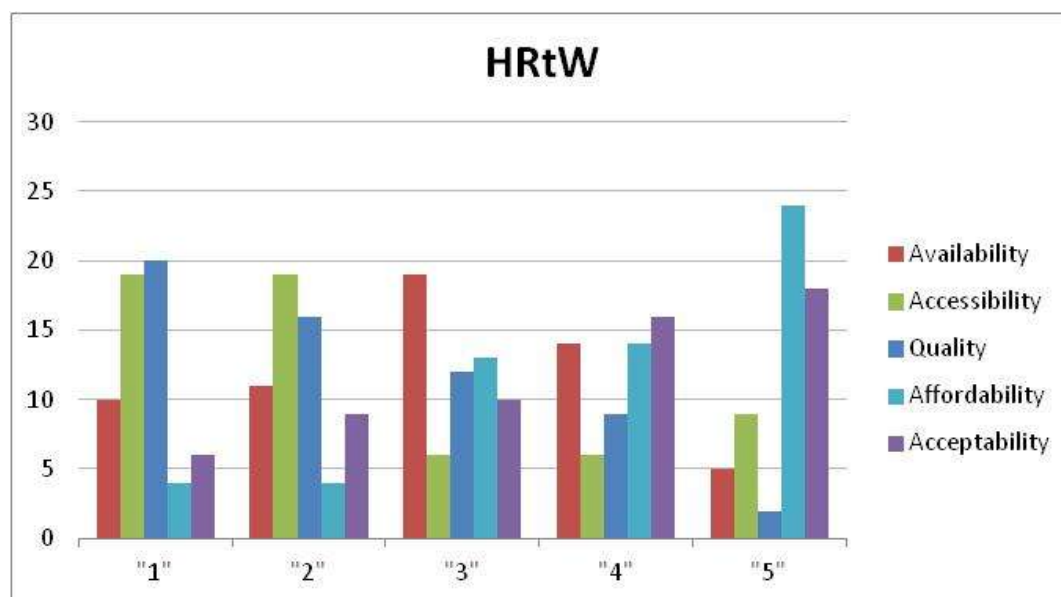
**Table 4** Comparison among the different management systems.

MANAGEMENT SYSTEM	PRICE (S/) / CILINDER	OBSERVATIONS
Community “Pilón”	Tanker truck: 2.16 (final price 2.30) SEDAPAL: 0.5 (final price 1)	- Additional fee charged by committee (community management) - Variable water availability
SEDAPAL	0.48	- Better water quality - Variable water availability
Tanker truck	To community “pilón”: 2–2.67 To household: 4.20	- Uncertain water quality - Variable water availability
Community members	Variable price (most expensive option)	- Greater difficulty in terms of water accessibility

## 2.5. COLLIQUE AND HRTWS

This overview finishes by briefly presenting a research work carried out with a limited number of Collique inhabitants. This work aimed to obtain information from all areas of Collique through the opinion of different population groups (children, youth, and women), to generate a proposal of indicators that measure water service levels taking into account a HRtWS approach and its five dimensions.

To achieve this objective, a series of participatory workshops were held, selecting different age groups of population. Thus, a qualitative analysis on water services (and sanitation) perception of the participants was obtained. The outcomes of these workshops resulted in 59 individual prioritizations associated with the dimensions of the Human Right to Water (HRtW).



**Figure 9** Responses in relation to the prioritization among HRtW dimensions. Priority order is shown on the x-axis. On the y-axis, the number of answers for each dimension was prioritized for each position.

As a result, the order of the dimensions provided by the participants was as follows:

**Table 5** Dimension prioritization with respect to Human Right to Water.

HRtW prioritization				
1	2	3	4	5
Quality	Accessibility	Availability	Acceptability	Affordability

From this qualitative research and a literature review, we propose a multidimensional index *i* based on five dimensions of HRtW. For each dimension, five service levels have been defined according to numerical values, with 1 the most optimal situation, and 0, the least optimal situation. This index, although applied to the specific case of Collique, could serve as the basis for carrying out the same multidimensional assessment in any context, allowing any comparison that is considered appropriate. The concepts of each category are shown in *Table 6*, and the different level of service for each category, in *Table 7*.

**Table 6** Service level definition according to the five dimensions of HRtW.

HRtW category definition: water service level				
Availability (AVA)	Accessibility (ACC)	Quality (QUA)	Affordability (AFF)	Acceptability (ACP)
Enough water and continuous supply	Nearby water and easy to obtain	Water apt for human consumption	Affordable water for all	Water acceptable in color, smell, and taste

**Table 7** Proposal of service levels for the five dimensions of HRtW.

HRtW conceptual framework proposal: water service level					
Level	Availability (AVA)	Accessibility (ACC)	Quality (QUA)	Affordability (AFF)	Acceptability (ACP)
1	24-hour on-premise service	Service on-premise with intra-household facilities in use (B)	Service on-premise or by "pilón" (supplied by Sedapal), apt for human consumption; storage recipients cleaned appropriately and frequently	Service Provision Utility (SPU) tariff, fixed or by consumption (without meter), which is fair and affordable according to purchasing power (G)	Water with mountain spring appearance, transparent, without a bad smell or chlorine taste
0.75	Service on-premise, continuity of 7 to 24 hours, with sufficient storage capacity (A)	Service on-premise without intra-household facilities (C)	Service on-premise or by "pilón" (supplied by Sedapal); water is boiled before consumption (D)	SPU tariff, fixed or by consumption (without meter), which represents an important part of the expenses for basic services	Transparent water but with a slight chlorine taste
0.50	Service on-premises, from 2 to 7 hours, supplied by "pilón", tanker truck, or other means; sufficient storage capacity	Service through "pilón" or tanker truck, with storage tanks on the roof and intra-household facilities	Service through "pilón" (supplied by tanker truck) or Sedapal tanker truck (E)	Payment by cylinder from the "pilón" (10 to 15 times higher than the SPU price)	Whitish water with a strong chlorine taste
0.25	Service on-premise, from 2 to 7 hours, supplied by "pilón", tanker truck, or other means; insufficient storage capacity	Service through "pilón", tanker truck, or other means, without intra-household facilities	Service through "pilón" (supplied by tanker truck) or clandestine tanker truck; water presents turbidity or strange elements (F)	Payment by cylinder from the tanker truck or other (40 times higher than the SPU price)	Water turbid or with strange elements
0	Supply from surface water (e.g., rivers, ditches, etc.)				

A. Sufficient storage capacity means that there is enough space to store the necessary water to carry out the daily activities of the whole family.

B. Intra-household facilities in use means that there is a 24-hour continuous service or that there are storage tanks on the roof that allow water to be used through a pipe.

C. Without intra-household facilities means that the infrastructure does not exist or that it is not used because there is no 24-hour service continuity or because there are no storage tanks on the roof that allow its use.

D. Boiling water before consumption is based on doubts about its quality that can be either due to network cuts, or to not knowing whether hygiene measures in network and distribution tanks maintenance are correct or not.

E. Hygiene of the tankers trucks depends on their care and maintenance directly from the tanker owners. It is often not adequate. If the tanker truck is supplied by Sedapal, the water comes from the treatment plant and is collected with enough residual chlorine to reach the households with 0.5 mg/l of residual chlorine.

F. The water in Collique network is pumped to different tanks distributed throughout the area, and water is then distributed to the households from these tanks. If the tanks are not properly maintained, and when water is not available over 24 hours, the water that arrives to the households might be turbid or dirty after the system is restarted.

G. Affordability includes being able to pay for the construction of intra-household facilities and can also include receiving subsidies (when necessary).

We would like to note, after having introducing the conceptual framework, that the five dimensions are not weighted equally. Rather, a specific weight is assigned to each dimension according to the prioritization presented in *Table 4*. However, it is important to highlight that Human Rights principles point out the importance of evaluating all categories equally. In this case, there is no intention to belittle any dimension, but rather to propose a conceptual framework that reflects the specific needs of study area.

For weight definition, the methodology called "centroid" (Shepetukha & Olson, 2001) is applied, which proposes to define those weights once the order of the categories is available. This methodology assigns weight  $w_1$  as the most important,  $w_2$  as the second most important, and so forth.

$$w_1 = \frac{(1 + \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{k})}{k}$$



$$w_2 = \frac{(0 + \frac{1}{2} + \frac{1}{3} + \dots + \frac{1}{k})}{k}$$

$$w_k = \frac{(0 + 0 + 0 + \dots + \frac{1}{k})}{k}$$

The sum of these weights will be equal to the unit. The more categories there are, the lower the implied error will be (Shepetukha & Olson, 2001). For the five categories that correspond to the HRtW five dimensions, the following weights are obtained (*Table 7*):

**Table 7** *Weights ordered for HRtW according to the proposed methodology.*

Quality (QUA)	Accessibility (ACC)	Availability (AVA)	Acceptability (ACP)	Affordability (AFF)
$w_1$	$w_2$	$w_3$	$w_4$	$w_5$
0.45	0.26	0.16	0.09	0.04

Finally, the multidimensional index is formulated based on the geometric (or multiplicative) mean of the different dimensions. It is very important to keep in mind that this formulation does not allow any compensation among the variables. That is, if any of the dimensions is evaluated as zero, the final value of the index will be zero as well.

$$\text{Index}_{\text{HRtW}} = \text{QUA}^{w_1} \times \text{ACC}^{w_2} \times \text{AVA}^{w_3} \times \text{ACP}^{w_4} \times \text{AFF}^{w_5}$$

Substituting both the values of the service level associated with the context of Collique and the values of the weights, the final value of the proposed index is obtained:

$$\text{Index}_{\text{HRtW}} = 0.5^{0.45} \times 0.25^{0.26} \times 0.25^{0.16} \times 0.5^{0.09} \times 0.25^{0.04} = 0.37$$

### 3. CLASS ACTIVITY

The class activity proposed in this case study is structured in two different blocks:

**Block I.** Students will work in small groups of 3 to 4 people. Afterwards, a general debate will take place. The duration of this activity is estimated to be 1 hour and 15 minutes: 45 minutes of group discussion and 30 minutes of general discussion. It is suggested that the professor acts as moderator.

To facilitate the development of this block and successive activities, it is recommended that students receive all the information presented in Section 2. Ideally, the contextualization of the case study should be provided before the development of the activities in order to provide adequate time for reading.

**Block II.** This is a workshop guided by the professor, in which students should work individually. This block takes an estimated 45 minutes to complete. Specifically, the workshop consists in providing the students with enough information to perform the dimensioning of a small water supply network. The objective is to be able to scale this design to a larger area (as homework activity).

## BLOCK I

The objective of this first activity is to raise awareness about the importance of accessing water services. This exercise will be carried out from a Human Rights perspective. In this sense, and after having presented the theoretical content of this case study, it is proposed to complete the attached table, by indicating the direct and indirect impacts associated with the deprivation of the HRtW dimensions. Impacts can be identified from different perspectives, such as health, development, and environment, among others. Likewise, each group is encouraged to identify and to justify the dimension that they consider to be the most important. Finally, and based on the current situation of Collique (service level) and the prioritization carried out, it is proposed that the students recalculate the proposed  $\text{Index}_{\text{HRtW}}$ .

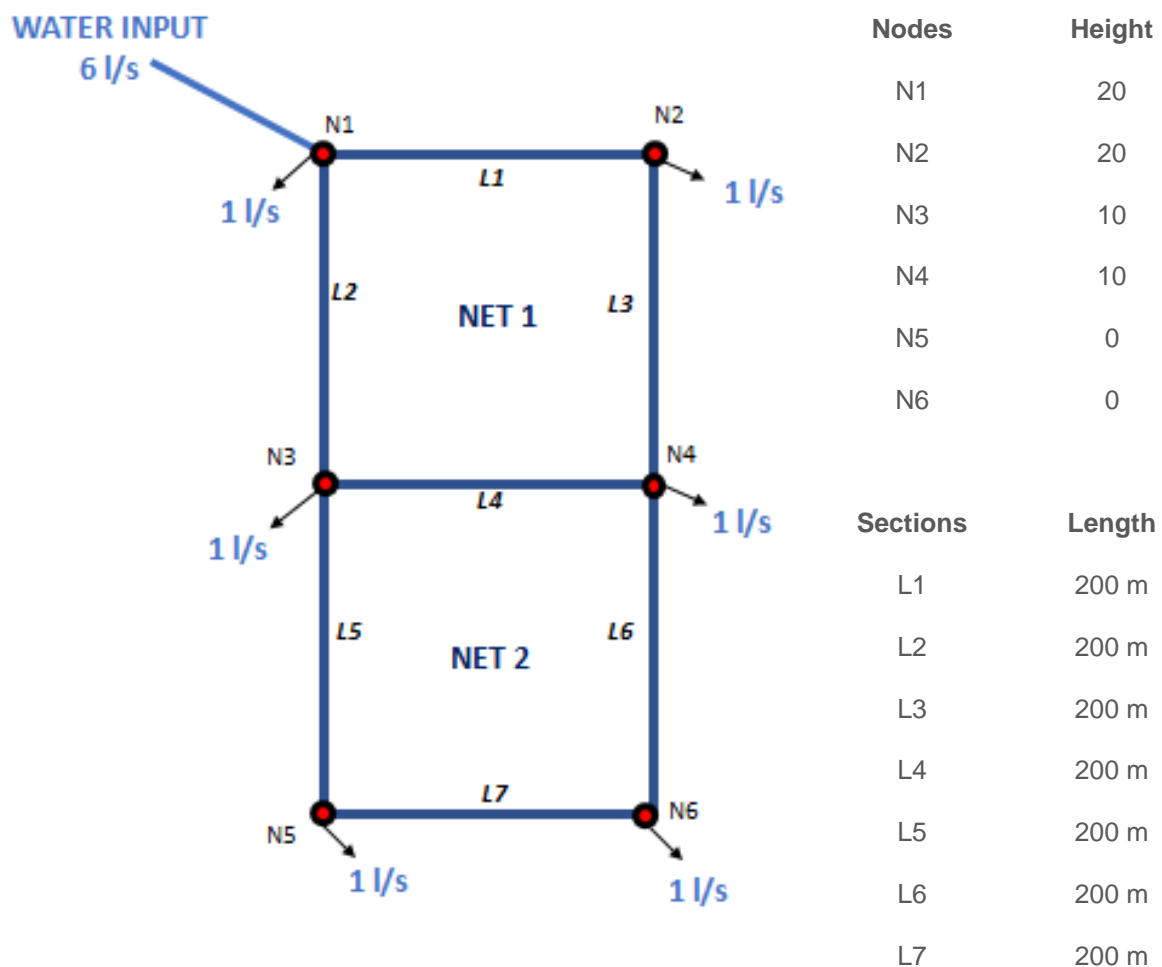
Ranking	DIMENSION (lack)	DIRECT IMPACTS	INDIRECT IMPACTS
	<b>Availability</b>		
	<b>Accessibility</b>		
	<b>Quality</b>		
	<b>Affordability</b>		
	<b>Acceptability</b>		

## BLOCK II

The aim of this guided workshop is to provide students with an illustrative example of the dimensioning of a small water supply network. Thus, the homework activity should be carried out autonomously.

The approach of this workshop will be at individual level. In this sense, it is expected that students will be able to follow and materialize the relevant calculations explained by the professor. The background and starting data are the following:

A drinking water distribution network should be dimensioned for the neighborhood of Collique that covers two blocks of  $200\text{ m} \times 200\text{ m}$ . The water input that feeds the meshes is located 20 m above nodes 1 and 2. In each node, there is a hydrant with a peak demand of 1 l/s, so that the consumption of the net is 6 l/s. In addition, all the sections are formed by equal pipes of 90 mm exterior diameter. The meshes that make up the network are square and equal, as shown in the following figure:



With this starting data, the students should calculate the internal flow of the network and the pressure that each hydrant will have, taking into account the pressure losses of pipe sections.

### 3.1. SOLUTION AND EVALUATION CRITERIA

#### Class activity solution: Block I

It must be taken into account that the answers are open (i.e., no set answers that are right or wrong), especially for the proposal of the HRtW dimension prioritization. This of course does not mean that the students (who are also possibly inexperienced in the subject) are always “right” with their reflections; rather, the mere task of reflecting is one of the objectives of this activity. Nonetheless, we have presented some possible answers here in order to guide the professor (moderator) during the general debate.

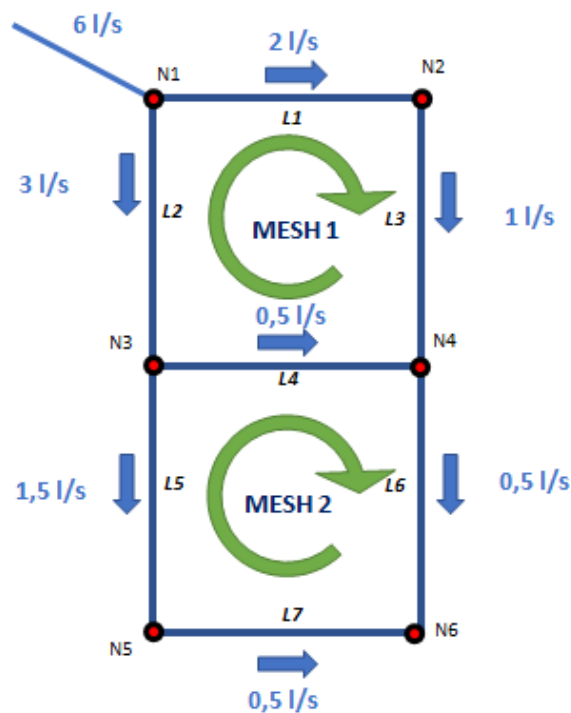
DIMENSION (lack)	DIRECT IMPACTS	INDIRECT IMPACTS
<b>Availability</b>	- Needs cannot be met when needed (drinking and cooking, hygiene, washing food and clothes)	- Economic investment in household deposits, for example, for storage
<b>Accessibility</b>	- Water needed for consumption (drinking and cooking, hygiene, washing food and clothes) cannot be guaranteed in cases when the water source is very far away - Leads to increased insecurity (especially when women and girls collect the water and when distances are long)	- Difficulty for the development of vital and economic activities  - Possibility of increasing aggression against girls and women
<b>Quality</b>	- Effects on human health (including death) - Deterioration of ecosystems (pollution)	- Difficulty to develop capacities (poverty growth); health expenditures increase - Decreased resources for subsistence (decreased food security and increased poverty)
<b>Affordability</b>	- Discrimination against the most unfavorable population sectors  - Possible generation of social conflicts	- Difficult to access to other services; increase in the gap between those who have more and those who have less - Increase in the gap between public institutions or agents responsible for the management of the service; decrease in citizen participation
<b>Acceptability</b>	- Search for alternative water sources (possible synonymous with health risk)	- Expenditure increase household and public health levels

As far as ranking elaborations and new index recalculations, each group is expected to will its own result. Therefore, no specific answer is provided for this section.

## Class activity solution: Block II

First, it is necessary to consider an internal water flow distribution to the mesh that meets each hydrant demand. Likewise, a water circulation direction of the mesh is established to identify the sign (positive or negative) of the flows in each section. The detailed procedure is shown in *Annex II*.

Additionally, the necessary iterations will be performed to obtain a residual ( $\Delta Q$ ) of zero. In this case, 2 and 3 iterations will suffice for mesh 1 and mesh 2, respectively.



### Mesh 1

STARTING DATA						
Section	$D_{ext}$ (mm)	$D_{int}$ (mm)	L (m)	Roughness	$r_i$ (mm)	$Q_1$ (m <sup>3</sup> /s)
L1	90	73.6	200	150	65,313.9	0.0020
L2	90	73.6	200	150	65,313.9	-0.0030
L3	90	73.6	200	150	65,313.9	0.0010
L4*	90	73.6	200	150	65,313.9	0.0005

ITERATION 1			ITERATION 2		
$\Delta h$	$\Delta h/Q_1$	$Q_2 = Q_1 + \Delta Q$	$\Delta h$	$\Delta h/Q_2$	$Q_3 = Q_2 + \Delta Q$
0.66	327.70	0.0023	0.851	369.56	0.0023
-1.39	462.93	-0.0027	-1.140	422.77	-0.0027
0.18	181.55	0.0013	0.296	227.49	0.0013
-0.05	100.58	-0.0005	-0.054	104.07	-0.0006
$\Sigma \Delta h$	$\Sigma(\Delta h/Q_i)$	$\Delta Q$	$\Sigma \Delta h$	$\Sigma(\Delta h/Q_i)$	$\Delta Q$
-0.6	1,072.77	0.0003	-0.047	1,123.90	0.0000

### Mesh 2

STARTING DATA						
Section	$D_{ext}$ (mm)	$D_{int}$ (mm)	L (m)	Roughness	$r_i$ (mm)	$Q_1$ (m <sup>3</sup> /s)
L4*	90	73.6	200	150	65,313.9	0.0005
L5	90	73.6	200	150	65,313.9	-0.0015
L6	90	73.6	200	150	65,313.9	0.0005
L7	90	73.6	200	150	65,313.9	-0.0005

ITERATION 1			ITERATION 2			ITERATION 3		
$\Delta h$	$\Delta h/Q_1$	$Q_2 = Q_1 + \Delta Q$	$\Delta h$	$\Delta h/Q_2$	$Q_3 = Q_2 + \Delta Q$	$\Delta h$	$\Delta h/Q_3$	$Q_4 = Q_3 + \Delta Q$
0.05	100.58	0.0005	0.0005	0.054	104.07	0,065	113,18	0,0006
-0.38	256.47	-0.0012	-0.0012	-0.245	208.53	-0,217	196,94	-0,0011
0.05	100.58	0.0008	0.0008	0.127	153.86	0,149	165,93	0,0009
-0.05	100.58	-0.0002	-0.0002	-0.007	41.43	-0,003	25,57	-0,0001
$\Sigma \Delta h$	$\Sigma(\Delta h/Q_i)$	$\Delta Q$	$\Sigma \Delta h$	$\Sigma(\Delta h/Q_i)$	$\Delta Q$	$\Sigma \Delta h$	$\Sigma(\Delta h/Q_i)$	$\Delta Q$
-0.33	558.22	0.0003	-0.072	507.89	0.0001	-0,005	501,63	0,0000

\*L4 section belongs to both meshes.

At the calculation level, the iteration would be as follows:

### Mesh 1

#### Section 1

$$Q_2(1) = Q_1(1) + \Delta Q_1(1) = 2.0 + 0.3 = 2.3 \text{ l/s}$$

$$Q_3(1) = Q_2(1) + \Delta Q_2(1) = 2.3 + 0.0 = 2.3 \text{ l/s}$$

$$Q_4(1) = Q_3(1) + \Delta Q_3(1) = 2.3 + 0.0 = 2.3 \text{ l/s}$$

#### Section 2

$$Q_2(1) = Q_1(1) + \Delta Q_1(1) = -3.0 + 0.3 = -2.7 \text{ l/s}$$

$$Q_3(1) = Q_2(1) + \Delta Q_2(1) = -2.7 + 0.0 = 2.7 \text{ l/s}$$

$$Q_4(1) = Q_3(1) + \Delta Q_3(1) = -2.7 + 0.0 = 2.7 \text{ l/s}$$

#### Section 3

$$Q_2(1) = Q_1(1) + \Delta Q_1(1) = 1.0 + 0.3 = 1.3 \text{ l/s}$$

$$Q_3(1) = Q_2(1) + \Delta Q_2(1) = 1.3 + 0.0 = 1.3 \text{ l/s}$$

$$Q_4(1) = Q_3(1) + \Delta Q_3(1) = 1.3 + 0.0 = 1.3 \text{ l/s}$$

#### Section 4

$$Q_2(1) = Q_1(1) + \Delta Q_1(1) - \Delta Q_1(2) = -0.5 + 0.3 - 0.3 = -0.5 \text{ l/s}$$

$$Q_3(1) = Q_2(1) + \Delta Q_2(1) - \Delta Q_2(2) = -0.5 + 0.0 - 0.1 = -0.6 \text{ l/s}$$

$$Q_4(1) = Q_3(1) + \Delta Q_3(1) - \Delta Q_3(2) = -0.6 + 0.0 - 0.0 = -0.6 \text{ l/s}$$

### Mesh 2

#### Section 4

$$Q_2(2) = Q_1(2) + \Delta Q_1(2) - \Delta Q_1(1) = 0.5 + 0.3 - 0.3 = 0.5 \text{ l/s}$$

$$Q_3(2) = Q_2(2) + \Delta Q_2(2) - \Delta Q_2(1) = 0.5 + 0.1 - 0.0 = 0.6 \text{ l/s}$$

$$Q_4(2) = Q_3(2) + \Delta Q_3(2) - \Delta Q_3(1) = 0.6 + 0.0 - 0.0 = 0.6 \text{ l/s}$$

#### Section 5

$$Q_2(2) = Q_1(2) + \Delta Q_1(2) = -1.5 + 0.3 = -1.2 \text{ l/s}$$

$$Q_3(2) = Q_2(2) + \Delta Q_2(2) = -1.2 + 0.1 = -1.1 \text{ l/s}$$

$$Q_4(2) = Q_3(2) + \Delta Q_3(2) = -1.1 + 0.0 = -1.1 \text{ l/s}$$

#### Section 6

$$Q_2(2) = Q_1(2) + \Delta Q_1(2) = 0.5 + 0.3 = 0.8 \text{ l/s}$$

$$Q_3(2) = Q_2(2) + \Delta Q_2(2) = 0.8 + 0.1 = 0.9 \text{ l/s}$$

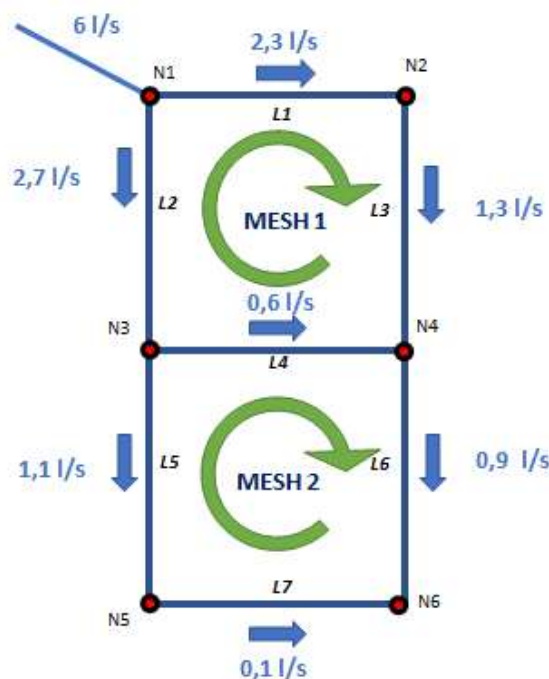
$$Q_4(2) = Q_3(2) + \Delta Q_3(2) = 0.9 + 0.0 = 0.9 \text{ l/s}$$

#### Section 7

$$Q_2(2) = Q_1(2) + \Delta Q_1(2) = -0.5 + 0.3 = -0.2 \text{ l/s}$$

$$Q_3(2) = Q_2(2) + \Delta Q_2(2) = -0.2 + 0.1 = -0.1 \text{ l/s}$$

$$Q_4(2) = Q_3(2) + \Delta Q_3(2) = -0.1 + 0.0 = -0.1 \text{ l/s}$$



As it can be seen in section 4, which belongs to both meshes, the calculation is balanced by taking the  $\Delta Q$  of each mesh, but of an opposite sign. Thus, the final result of the flow within the mesh is presented above.

Once the solution of the flows in each section has been found, it is necessary to determine the pressure losses to guarantee that the pressure in each node is adequate (between 30 and 60 meters water column). Likewise, circulation velocities must be checked so that they are included between the values 0.6 and 1 m/s (see *Annex I*).

Section	D <sub>ext</sub> (mm)	D <sub>int</sub> (mm)	L (m)	Rough.	Q (l/s)	v (m/s)	H (m)	$\Delta z$ (m)	P (mwc)
1	90	73.6	200	150	2.33	0.55	0.87	40	39.13
2	90	73.6	200	150	2.67	0.63	1.12	40	38.88
3	90	73.6	200	150	1.33	0.31	0.31	50	49.69
4	90	73.6	200	150	0.57	0.13	0.06	50	49.94
5	90	73.6	200	150	1.09	0.26	0.21	50	49.79
6	90	73.6	200	150	0.91	0.21	0.15	60	59.85
7	90	73.6	200	150	0.09	0.02	0.00	60	60.00

### Evaluation criteria

To evaluate this class activity, the use of the attached rubric is proposed (see *Annex VII*). Briefly, this rubric details: i) the knowledge that students are expected to acquire, and ii) the criteria that will be used to evaluate the resolution content associated with the activities proposed. This way helps to provide an objective and transparent evaluation system for the students.

Firstly, students should be informed about the existence of the rubric. That is, they must be provided the rubric along with the information related to the contents to be evaluated. Thus, some guidance should be given to students to allow them to carry out the proposed activities.

For the evaluation of Block I, each group must submit a written document answering the questions raised. These answers will be evaluated based on the proposed rubric. However, the professor is free to choose an alternative evaluation method if she/he considers it more appropriate. On the other hand, Block II will not be evaluated, as it is a guided workshop with



the sole objective of providing the necessary knowledge to develop the autonomous activity that is proposed.

#### 4. HOMEWORK ACTIVITY

In this activity, students will work in small groups of 3 to 4 people (note that maintaining the same working groups as in the previous activity would make it easier to evaluate the overall work). The main reason for group work is to encourage internal debate. The activity is estimated to require approximately 15 to 20 hours of work.

From a more technical perspective, and in methodological terms, it is proposed to solve the exercise through the use of an excel spreadsheet, posing the problem in a simplified manner but considering the main phenomena for dimensioning the water supply network. However, the existence of specific software for hydraulic networks calculation should be highlighted. In this sense, it is possible to find the tool which is presented under the name of EPANET<sup>2</sup> and is distributed openly by the Environmental Protection Agency (EPA) of the United States. In addition, and in contrast, a commercial tool named WaterGEMS<sup>3</sup>, developed by Bentley, can be found as well.

The aim of this activity encourages the students to apply the knowledge they acquired both through the guided workshop and through the contextualization of this case study. Specifically, the students are expected to be able to dimension a larger water distribution network and to be able to reflect on the service management. Under these premises, the problem that arises is the following.

In its eagerness to improve the level of water service, the government of the city of Lima (through the public company SEDAPAL) decides to expand the water supply network in the neighborhood of Collique. One of the agreements reached guarantees the execution of the work with the commitment of neighborhood residents, who should participate in the service management.

The final technical decision lies in the construction of a series of public water sources located in different parts of the neighborhood. The location criterion is to provide each household with access to a source located between 50 and 100 meters away.

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<sup>2</sup> Access and information regarding EPANET software at: <https://www.epa.gov/water-research/epanet>.

<sup>3</sup> More information as far as WaterGEMS commercial software at: <https://www.bentley.com/es/products/product-line/hydraulics-and-hydrology-software/watergems>

In order to simplify the problem, the focus in this case study will be directed to a limited set of households (see *Figure 10*), which belong to the upper part of zone 6 of Collique.



**Figure 10** Project service area. Source: Own elaboration, from Google Earth.

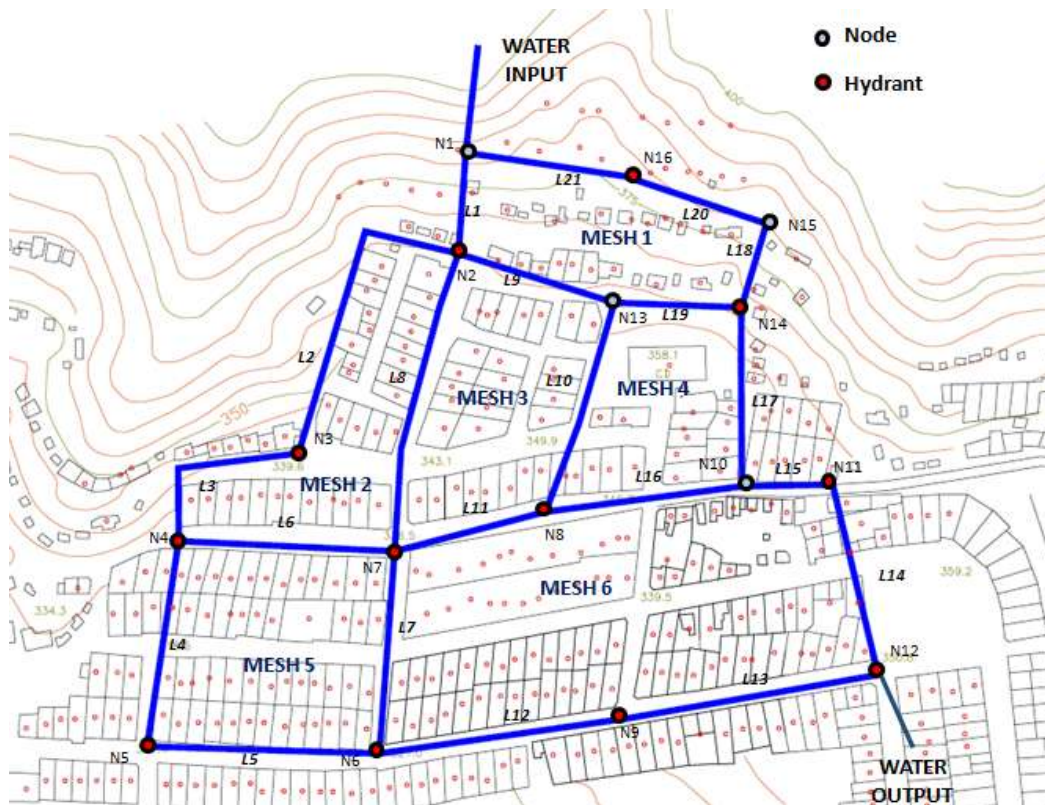
The designed water endowment is fixed at 120 l/inhabitant per day. The justification resides, on the one hand, in that endowments greater than 100 liters per day satisfy all the needs of consumption and hygiene, thus reducing the impact on health almost completely (WHO, 2003). On the other hand, it includes a more-than-likely consumption increase in the future.

Further, the service area is approximately 10.2 ha (hm<sup>2</sup>). Assuming a homogeneous population distribution in Collique, which has a population density of 23,200 inhabitants / km<sup>2</sup> (see *Table 3*), it can be estimated that 2,366 people live in the area. If a population growth of 1.5% per year is assumed, the predicted population in 2035 is estimated to be 3,187 inhabitants who live in the study area. Therefore, the starting data is detailed as follows:

**Table 8** Starting data for water distribution network dimension.

VARIABLE	VALUE
Current population	2,366 inhab
Estimated population in 2035	3,187 inhab
Daily consumption	382,464 L/day
Daily peak consumption (+10%)	38,246 L/day
Design flow	10.6 L/s

Therefore, a future peak flow of 10.6 l/s is estimated to be required to serve the study area. In addition to this, the geometry of the network must be defined. In this sense, a network with 6 meshes, 21 sections, and 16 nodes has been designed. The reason for choosing such geometry of redundant meshes lies in the possibility of guaranteeing flow circulation in case of breakage of any section. The system of water sources is distributed in 12 of network nodes, which will have an identical output flow rate of 0.883 l/s. The location of these hydrants has been made based on the accessibility criteria detailed above (see *Figure 11*).



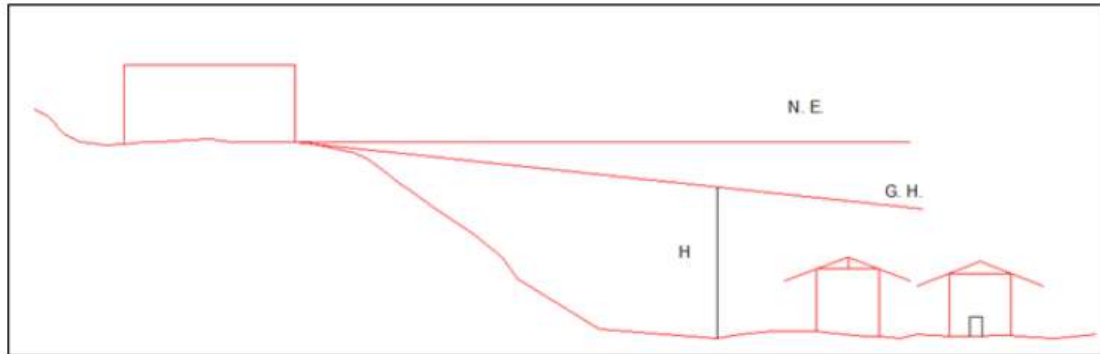
**Figure 11** Proposal for water distribution network geometry

Finally, data associated with network pipe sections and nodes are provided to support carrying out the activity.

SECTION	LENGTH (m)
L1	47.6
L2	146.3
L3	81.0
L4	94.7
L5	109.6
L6	101.9
L7	95.4
L8	141.2
L9	77
L10	103.7
L11	73.6

SECTION	LENGTH (m)
L12	117.8
L13	120.3
L14	92.2
L15	42.8
L16	93.4
L17	84.2
L18	41.2
L19	60
L20	70
L21	75.8

A storage tank will be built at water input point, located 8 meters above node N1. This height allows water to flow by gravity and to be distributed to the public water sources, overcoming the hydraulic gradient. The capacity of the deposit is estimated to be 1,000 m<sup>3</sup>. These data have no influence on dimensioning the distribution network but facilitate understanding of system operation.



**Figure 12** Height storage tank distribution scheme. Source: Jiménez Terán, 2013.

NODE	HEIGHT (m)	NODE	HEIGHT (m)
N1	382	N9	335
N2	360	N10	350
N3	360	N11	355
N4	333	N12	350
N5	311	N13	362
N6	321	N14	372
N7	336	N15	380
N8	340	N16	377

Once starting data for developing the proposed technical activity have been provided, students are required to reflect and state their response to the six questions indicated below. Additionally, students are requested to link these reflections to the ethical code of the profession. For this purpose, the given deontological codes can be taken as examples (see *Annexes III* and *IV*). However, similar documents can be used if convenient.

**Task 1.** Analyze and discuss the obtained technical results.

**Task 2.** Propose a management scheme related to the water distribution network (maximum 2 pages). In this proposal, it is suggested that students discuss aspects related to the organization among the residents of the neighborhood, the relationship with SEDAPAL, the control of the water supply (e.g., quality, consumption, etc.), the medium / long-term strategy, the potential actions regarding the most vulnerable populations in the neighborhood, transfer of knowledge, etc. Additionally, and from an ethical point of view, students should reflect about the need / responsibility of the engineer to participate in the process of defining the management system.



**Task 3.** Detail the possible reasons why a project to bring water into household premises has not been carried out.

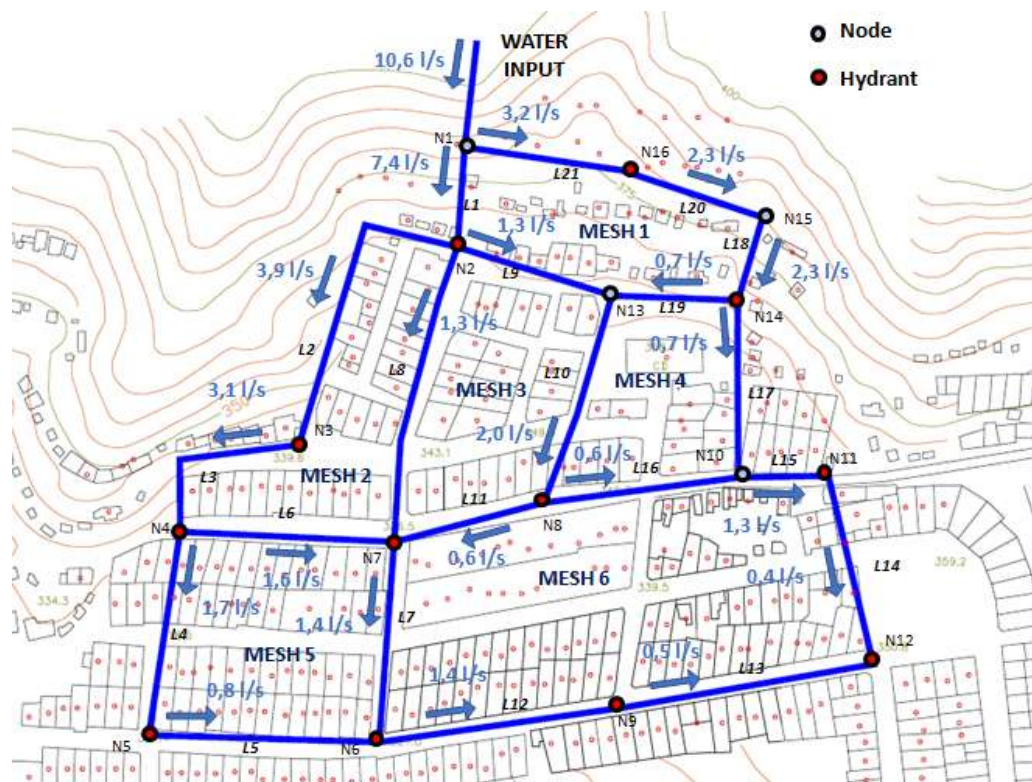
**Task 4.** If a distinct ethical code of the profession is used for consultation, briefly compare the main similarities and differences with those codes that have been provided herein (*Annexes III and IV*).

**Task 5.** Compare the result of building public water sources and household connections from the perspective and methodology of the multidimensional index proposed ( $\text{Index}_{\text{HRTW}}$ ). For this purpose, students should rely on the conceptual proposal outlined in *Table 7*.

**Task 6.** Reflect on the suitability of using the proposed multidimensional index to assess the level of water service. Do you consider that the HRTW dimensions should be included to evaluate the performance of a service provider, such as SEDAPAL? Evaluate the pros and cons of implementing this proposal.

#### 4.1. SOLUTION Y EVALUATION CRITERIA

Hydraulic calculations must be carried out for each section. To do this, a first assumption of each mesh flow distribution should be done, assigning random flow directions. These flows and directions will serve to perform the first iteration of the calculation process. Possible flow distributions could be the following:

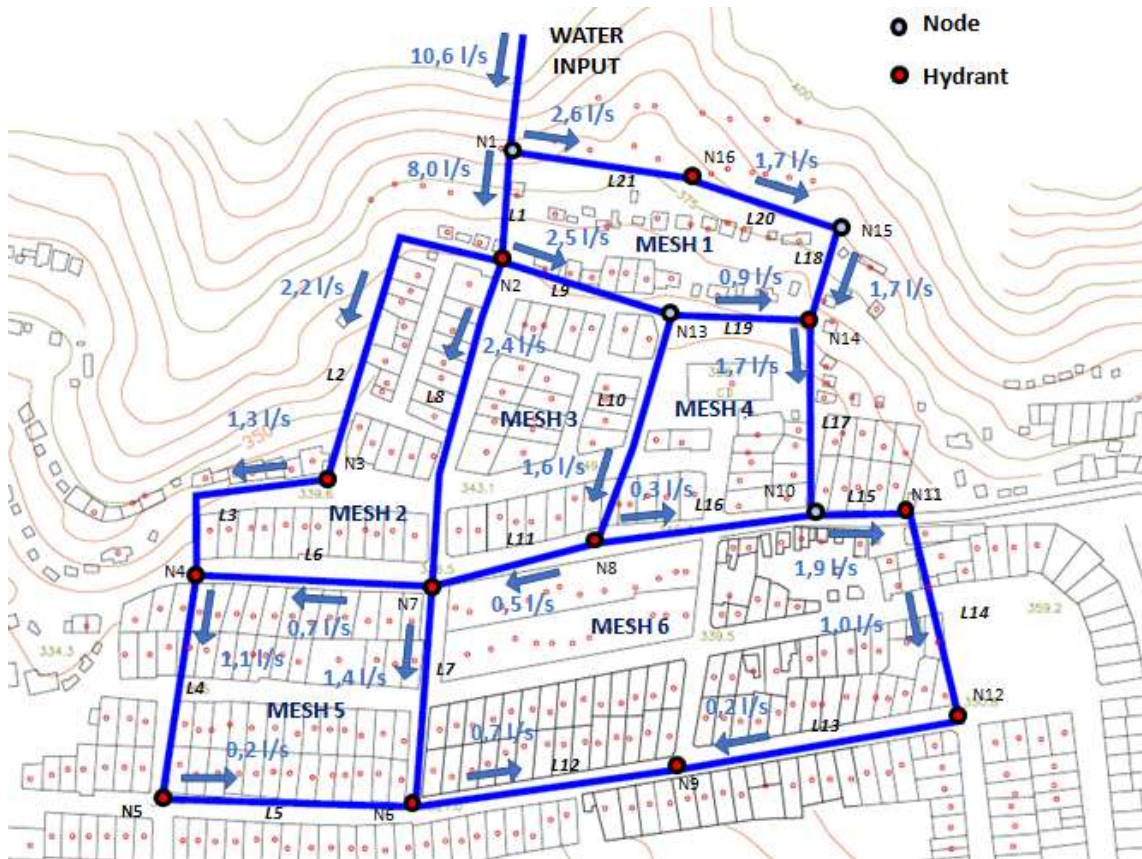


For pipe diameter calculation, the Hardy-Cross iterative method should be used (see *Annex I*). First, a flow equilibrium is made among the nodes, and the theoretical internal diameter ( $D_t$ ) is calculated. Once  $D_t$  has been obtained, the nearest commercial diameter, which guarantees specific velocities, is chosen. For example, if a velocity of 0.5 m/s is reached, the commercial diameter with the smallest radius (in this case, 90 mm) will be chosen. In this way, the results obtained are presented in the following table:

REQUIRED DIAMETER ESTIMATION						
Node	Q (l/s)	v (m/s)	D <sub>int</sub> (mm)	D <sub>int</sub> comer. (mm)	D <sub>ext</sub> comer. (mm)	Check v
1	10.623	1,00	116.30	130.80	160 (P.N.16 ESP.)	0.79
2	6.551	1,00	91.33	114.60	140 (P.N.16 ESP.)	0.64
3	3.045	1,00	62.27	73.60	90 (P.N.16 ESP.)	0.72
4	2.160	1,00	52.44	73.60	90 (P.N.16 ESP.)	0.51
5	0.843	1,00	32.76	73.60	90 (P.N.16 ESP.)	0.20
6	1.381	1,00	41.93	73.60	90 (P.N.16 ESP.)	0.32
7	1.424	1,00	42.57	73.60	90 (P.N.16 ESP.)	0.33
8	1.133	1,00	37.98	73.60	90 (P.N.16 ESP.)	0.27
9	0.496	1,00	25.12	73.60	90 (P.N.16 ESP.)	0.12
10	1.275	1,00	40.29	73.60	90 (P.N.16 ESP.)	0.30
11	0.390	1,00	22.27	73.60	90 (P.N.16 ESP.)	0.09
12	0.000	1,00	---	73.60	90 (P.N.16 ESP.)	0.00
13	2.018	1,00	50.69	73.60	90 (P.N.16 ESP.)	0.47
14	1.416	1,00	42.47	73.60	90 (P.N.16 ESP.)	0.33
15	2.302	1,00	54.14	73.60	90 (P.N.16 ESP.)	0.54
16	2.302	1,00	54.14	73.60	90 (P.N.16 ESP.)	0.54

Once these values have been obtained, the iteration process, explained in the guided workshop, will be carried out. For this, as mentioned, an Excel spreadsheet will be used as support, due to the large number of operations and iterations (minimum 5 per mesh).

The result of the iteration process is the following:



As in the guided workshop, it would be necessary to determine the pressure losses (to guarantee that the pressure in each node is adequate) as well as the circulation velocities.

Section	D <sub>ext</sub> (mm)	D <sub>int</sub> (mm)	L (m)	Rough.	Q (l/s)	v (m/s)	H (m)	Δz (m)	P (mwc)
1	140	114.6	47.6	150	8.04	0.78	0.24	22	29.76
2	90	73.6	146.3	150	2.22	0.52	0.58	22	29.42
3	90	73.6	81	150	1.33	0.31	0.13	49	56.87
4	90	73.6	94.7	150	1.12	0.26	0.11	47	54.89
5	90	73.6	109.6	150	0.24	0.06	0.01	61	68.99
6	90	73.6	101.9	150	0.68	0.16	0.04	61	68.96
7	90	73.6	95.4	150	1.37	0.32	0.16	61	68.84
8	90	73.6	141.2	150	2.42	0.57	0.66	46	53.34
9	90	73.6	77	150	2.52	0.59	0.39	20	27.61

Section	D <sub>ext</sub> (mm)	D <sub>int</sub> (mm)	L (m)	Rough.	Q (l/s)	v (m/s)	H (m)	Δz (m)	P (mwc)
10	90	73.6	103.7	150	1.65	0.39	0.24	42	49.76
11	90	73.6	73.6	150	0.51	0.12	0.02	46	53.98
12	90	73.6	117.8	150	0.72	0.17	0.06	47	54.94
13	90	73.6	120.3	150	0.16	0.04	0.00	32	40.00
14	90	73.6	92.2	150	1.05	0.25	0.09	32	39.91
15	90	73.6	42.8	150	1.93	0.45	0.13	27	34.87
16	90	73.6	93.4	150	0.25	0.06	0.01	42	49.99
17	90	73.6	84.2	150	1.68	0.39	0.20	32	39.80
18	90	73.6	41.2	150	1.69	0.40	0.10	10	17.90
19	90	73.6	60	150	0.87	0.21	0.04	15	22.96
20	90	73.6	70	150	1.69	0.40	0.17	2	9.83
21	90	73.6	75.8	150	2.58	0.61	0.40	5	12.60

**Discussion for Task 1.** Once dimensioning has been done, students were requested to analyze and discuss the technical results obtained.

One of the first remarkable aspects is the existence of certain pipe sections (i.e. sections 9, 18, 19, 20, and 21, corresponding to the net 1) in which water pressure is not between the values cited above (i.e., between 30 and 60 mwc). These design values serve to ensure network pressures in the case of several height buildings without the need for additional installations. Regarding Collique's current urbanization and proposed distribution system of water sources, lower pressures are admitted, as water distribution is made at ground level.

As the network has been dimensioned to support a future distribution to household premises, it must be taken into account that, in those dwellings located at the top of the neighborhood, the pressure is less than 30 mwc. If the upper buildings in the area have more than two floors, it is likely that water pumps will be needed to supply upper floors. Currently, the highest areas of Collique are the ones with most precarious constructions, with only a ground floor (see *Figure 4*). For this reason, the calculated pressures guarantee water service at these heights.



Some sections, which correspond to lower heights, have pressures greater than 60 mwc. It is recommended that these pressures are lower than this value, in order to have a margin of safety for the different elements of the network (such as for joints, pipes, valves, etc.). In those sections in which desired pressure is exceeded, values between 10% and 15% are reached. Although the different material components that make up the network are usually designed to withstand pressures of 100 mwc, it is important to consider these high pressures to foresee the possible installation of regulators throughout the network.

The different mechanical components of a distribution network have not been addressed in this case study; therefore, the problem is limited to the flow and mesh balance calculations, rather than to the constructive procedures of the network itself. In spite of this, other technical considerations must be taken into account that are complementary to those set out above (e.g. other aspects dealt with in the subject).

However, the network is far from the maximum operating values. Water circulation velocities do not reach the value of 1 m/s, which is considered to be the optimum value when dimensioning for a given pipe diameter. Therefore, the resulting network could absorb an increase in demand. To corroborate this statement, the students are recommended to perform an exercise in which the inflow is doubled and the meshes are readjusted (if necessary). In the event that the neighborhood has grown in size and population, not only the increased consumption but also the entrance pressure to the proposed distribution network must be reviewed.

Finally, it can be observed that practically all the pipes used (except for section 1, due to a higher inflow rate) have the same commercial size (90 mm exterior diameter). Notably, using same pipe diameters is useful for both construction and maintenance reasons.

**Discussion for Task 2.** For the management scheme that is requested, it should be noted that it is an open response with no single “correct” solution. Therefore, no specific example is provided for this.

However, as mentioned previously, students are expected to reflect from two different points of view: I) in those aspects related to the service management itself (organization among residents, relationship with SEDAPAL, control of water supply, etc.); and II) considering professional activity from an ethical point of view. In this sense, and starting from the proposed solution, students are expected to establish links with environmental, social, and economic aspects with the ethical code they have used.

**Discussion for Task 3.** There may be several reasons why a project is not executed to provide households with water connections on-premise. In this light, and as for the previous question, this response is open; nonetheless, some possible lines of reflection are detailed

here: I) a project of this nature has an associated greater complexity of execution and a greater economic cost. Specifically, in the dimensioned network, 1,822 m of pipe were used to distribute water to the public water sources (see *Annex VI*); II) the clear economic savings could be used to build a similar system elsewhere in the city with a situation similar to that of Collique. The objective would be to calculate the number of people who access the service in order to provide an optimal service to a smaller subset; III) the proposed solution pursues citizen participation in the service management. In this sense, the service provider's duties would be facilitated, and an increased awareness for all parties related to this service would be favored. However, this possible strategy would not be exempt from the appearance of possible conflicts between both parties.

**Discussion for Task 4.** If another ethical code of the profession has been used, students will be requested to identify those main aspects in which it coincides with and/or differs from the codes provided here as the example (*Annexes III and IV*). If the provided codes were used, answering this question is no longer relevant. The main objective of the question is for the students to know about, and to reflect on, the deontological code of the profession.

**Discussion for Task 5.** The quantitative results of the multidimensional index ( $\text{Index}_{\text{HRtW}}$ ) are presented below. Specifically, results refer to those cases in which Collique's population access to water through public water sources ("pilón") or directly on-premise. To define the values associated with HRtW dimensions, the conceptual framework proposed in *Table 7* of this document is used. The weights associated with each dimension are kept constant according to the research carried out in Collique.

For the results obtained, a clear difference between the two possible solutions can be seen. Taking into account that the current value is 0.37 (see *Section 2.5*), this valuation would increase 30% (0.52) by building public water sources, and by 60% (0.89) by providing access to water on household premises.

"PILÓN"	Quality (QUA)	Accessibility (ACC)	Availability (AVA)	Acceptability (ACP)	Affordability (AFF)
Value	0.5	0.25	0.75	0.5	0.75
Weight	$W_1$	$W_2$	$W_3$	$W_4$	$W_5$
	0.45	0.26	0.16	0.09	0.04
$\text{Index}_{\text{HRtW}}$	0.52				

ON PREMISES	Quality (QUA)	Accessibility (ACC)	Availability (AVA)	Acceptability (ACP)	Affordability (AFF)
Value	1	0.75	1	0.75	0.75
Weight	$W_1$	$W_2$	$W_3$	$W_4$	$W_5$
	0.45	0.26	0.16	0.09	0.04
<b>Index<sub>HRtW</sub></b>	<b>0.89</b>				

**Discussion for Task 6.** Although this question is also open to the opinions of the students, there are some aspects that should be considered. Positive aspects include the use of a common monitoring framework, such as the one proposed, as this would offer a closer view of reality, in line with the recognition of this service as a Human Right. Additionally, it would facilitate the comparison between different areas/regions, objectively supporting the prioritization around what to do and where to invest, and thereby making those sectors of the most vulnerable population more visible. Additionally, transparency would be promoted by the service provider. Negative include potential conflicts that could arise within the population if the assessment is low aspects (this depend on the students' results from this index). Moreover, obtaining and updating the information about the HRtW dimensions would mean an extra cost for the service provider, especially in the first years of implementation. Furthermore, this cost would be greater if the objective is to face the impacts described in the class activity as well. However, it must be said that this last aspect should not be the exclusive responsibility of the service provider.

Finally, the alignment with target 6.1 of SDG 6 is remarkable. Although there are certain differences with the indicators proposed at the international level, which do not include aspects of affordability and acceptability, this multidimensional index could represent a starting point to integrate all HRtW dimensions. However, it should be deepened in a more general proposal that could be used in different realities.

### Evaluation criteria

In order to evaluate this activity, a written report will be submitted (including the annex with the relevant calculations), solving all questions formulated in the activity.

For the evaluation of the report, the use of the previously mentioned rubric is recommended (see *Annex VII*). This instrument specifically identifies which aspects of the homework activity will be considered and how they will be assessed.

However, as mentioned above, the professor is free to choose an alternative evaluation method if she/he considers it more appropriate.

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## ANNEXES

- I. Parameters to be considered for the water network dimensioning  
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- II. Meshed network scheme calculations < A.II\_Meshed\_network\_calculations.pdf >
- III. Engineering code of ethics example (in Spanish)  
< A.III\_Ethics\_code\_industrial\_engineering.pdf >
- IV. Industrial engineering code of ethics example  
< A.IV\_Ethics\_code\_ASCE.pdf >
- V. Class activity calculations < A.V\_Class\_activity\_calculations.xlsx >
- VI. Homework activity calculations < A.VI\_Homework\_activity\_calculations.xlsx >
- VII. Evaluation rubric < A.VII\_Evaluation\_rubric.pdf >



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# Multivariate Analysis and Indices Construction: Data Mining Applied to the Rural Water and Sanitation Sector in Honduras

Camila Vergara Fuentes and Agustí Pérez Foguet



PHOTO: "Local engineering". Honduras. David Requejo-Castro



# CASE STUDIES **Multivariate Analysis and Indices Construction: Data Mining Applied to the Rural Water and Sanitation Sector in Honduras**

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# 6

## MULTIVARIATE ANALYSIS AND INDICES CONSTRUCTION: DATA MINING APPLIED TO THE RURAL WATER AND SANITATION SECTOR IN HONDURAS

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## 1. INTRODUCTION

Access to water, sanitation, and hygiene (WaSH) is essential for human development and well-being. These are not only objectives in and of themselves but are also critical for the achievement of other development objectives. However, too many people have no access to these basic services. This situation has been recognized by the Member States of the United Nations, who signed the Millennium Declaration in 2000, which led to the Millennium Development Goals (MDGs). Subsequently, in September 2015, a historic United Nations summit was held, and world leaders approved the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development. These new Objectives are people-based and should lead, over the next 15 years, to countries intensifying their efforts to end poverty in all its forms, reducing inequality, and fighting against climate change while guaranteeing, at the same time, that no one is left behind. Specifically, Goal 6 calls for guaranteeing, by 2030, the availability of water, its sustainable management, and sanitation for all, with 8 additional proposed goals.

In order to achieve these objectives, it has been necessary to develop a global strategy and to define which factors should be considered, and how this should occur, with the aim of providing some guidance in the application of possible actions. In this context, indicators and indices play a key role, providing information that allows some questions to be answered that are related to what, how, where, and who should act.

In this case study, a current situation regarding the access to water and sanitation will be introduced, showing how monitoring of the sector has evolved in recent years. Secondly, a specific approach to the Honduran reality will be provided. Finally, the necessary information related to its water and sanitation sector situation and work context (database Lempira Department, Honduras) will be provided to execute the proposed activities.

### 1.1. DISCIPLINES COVERED

The main discipline addressed in this case study is the analysis of real data through statistical techniques, including Principal Component Analysis (PCA) and Multiple Linear Regression (MLR), according to the available information (e.g., data and quantitative assessments). The objective is to improve the knowledge of these techniques and to apply them by using specialized software, analysing the data series, and interpreting the results. Based on these premises, a basic knowledge of statistics is considered indispensable.

No less important, aspects related to cooperation for development are also addressed. In

parallel, teamwork is promoted, as most of the proposed activities are to be carried out in small groups, which ultimately should stimulate a general debate in the classroom.

## 1.2. LEARNING OUTCOMES

As a result of this case study, it is expected that students will be able to:

- Understand the problem associated with the lack of access to drinking water and sanitation services, and its consequences for human development, as well as links with poverty;
- Understand how information management can support decision-making processes, such as the allocation of resources in a given study region;
- Apply statistical analysis on real data by using specialized statistical software, in addition to other basic statistical analysis;
- Understand statistical techniques such as PCA and MLR, in order to apply them to data analysis.

## 1.3. ACTIVITIES

The proposed work to carry out is based on two activities:

1) A first activity is designed to be done in the classroom and is divided into two blocks. In the first block, students are invited to reflect on the theoretical knowledge presented through the approach of various issues. The second block is a "workshop" in which the students will be guided in the application of basic statistics concepts, the methodology of PCA, the application of MLR, and the corresponding construction of indexes. This will be supported by using the free software R (version 1.0.143);

2) The second activity will be carried out autonomously but in small groups (of approximately 3 people). Basically, students will be encouraged to apply the concepts and methods learned in the first activity. However, a more in-depth analysis will be required for simulating decision-making processes related to the presented case study.

Each activity done with the support of the specific software comprises four parts:

- Part 0: Univariate and multivariate statistical analysis

- Part I: Application of unsupervised techniques
- Part II: Application of supervised techniques
- Part III: Reflection

## 2. CONTEXT

In this section, relevant information is provided to contextualize the case study. The first example highlights the evolution that the water and sanitation sector has experienced, in terms of monitoring. At the same time, latest global estimates are given in order to show the current situation of the sector. Secondly, the specific situation in Honduras is presented, highlighting aspects such as the governance of the sector. Finally, basic aspects of the Rural Water and Sanitation Information System (SIASAR, for the Spanish name *Sistema de Información de Agua y Saneamiento Rural*) are introduced as an initiative that spans 11 countries in Latin America and the Caribbean, and in which Honduras was involved from the beginning. Additionally, real data related to this information system are provided to carry out the proposed activities.

### 2.1. BRIEF HISTORY OF THE MONITORING OF WATER AND SANITATION ACCESS

Access to water, sanitation, and hygiene (WaSH) is essential for human development and well-being (Carter et al., 1999; Cairncross & Valdmanis, 2006). The improvement of these aspects is also essential for the achievement of other development objectives, such as adequate nutrition, gender equality, education, and poverty eradication (Joint Monitoring Program, 2015a). In this context, monitoring and evaluation are fundamental for decision-making, since governments, civil society, and donors need objective and reliable data on which to base planning, prioritization, and accountability mechanisms.

In 1977, the United Nations Conference on Water was held in Mar del Plata (Argentina), creating the first international initiative to monitor the state and trends associated with access to water and sanitation. As a consequence of this Conference, in which both high and low income countries prominently participated, the International Decade of Water Supply and Sanitation was declared for the 1981–1990 period. The overarching objective was the universal provision of safe water and sanitation. During this period, each country's government provided their own estimates for monitoring the progress achieved. Despite not achieving the goal of providing water and sanitation for all, important lessons were learned. On the one hand, the reliability of the data used was questioned (Cotton & Bartram, 2008).

In this sense, the need to base estimates on representative samples of the population was highlighted. On the other hand, the need for defining a joint monitoring framework was pointed out, from the perspective of "you cannot manage what you cannot measure" (Creech et al., 2002, cited by Giné-Garriga, 2015).

In response to these needs, the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) combined efforts in 1990 with the Joint Monitoring Program for Water Supply and Sanitation (JMP), whose main objective was and is to monitor national progress towards the universality of access to safe water and sanitation. Since then, the water and sanitation sector has undergone an important transition in the way the access to these services are assessed. Initially, the indicators employed basically quantified the mere access to water or sanitation infrastructure in terms of coverage. Progressively, the monitoring of the sector has been oriented to be carried out in broader terms of "level or quality of service" instead of in terms of "coverage" only. In fact, the term "level of service" has been widely discussed and used to categorize and differentiate between service qualities (Lloyd and Bartram, 1991; Howard and Bartram, 2003; Moriarty et al., 2011; Potter et al., 2011; Giné-Garriga et al., 2011; Giné-Garriga & Pérez-Foguet, 2013a).

In 2000, the Member States of the United Nations signed the Millennium Declaration, which led to the formulation of the Millennium Development Goals<sup>1</sup> (MDGs), which called the international community to halve, by 2015, the proportion of people without sustainable access to drinking water and basic sanitation services. During the first half of this period, and in order to improve the comparison of information between countries, JMP defined a series of criteria to describe the level of progress in water and sanitation service delivery. For access to water, and based on the technology used, it was assumed that some infrastructures were better than others. As a result, a "ladder" with three rungs was proposed to differentiate service levels defined as "not improved", "improved" and "piped on premises" (Joint Monitoring Program, 2008). For access to sanitation, and considering the wide range of existing technologies according to the context, the suitability (concept of "improved") of the infrastructure was defined as long as it was of private use and the excreta was separated hygienically from human contact (Joint Monitoring Program, 2008). As a result, a ladder with four rungs was presented: "open defecation" (lower step), "not improved", "shared", and "improved" (upper step). In this sense, only those people with access to "improved" water and sanitation services were considered to be "covered". During the MDG period, important advances were made. However, in 2015, estimates showed that 663 million people around the world still used unimproved sources of drinking water, and that 2,400 million people used unimproved sanitation facilities. At the same time, it was estimated that 79% of those people

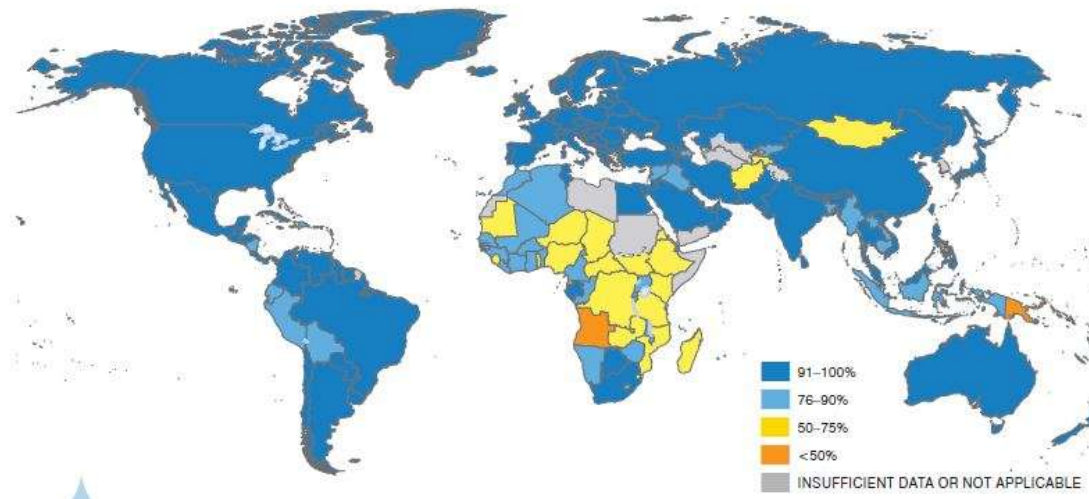
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<sup>1</sup> More information available at: <http://www.un.org/es/millenniumgoals/bkgd.shtml>



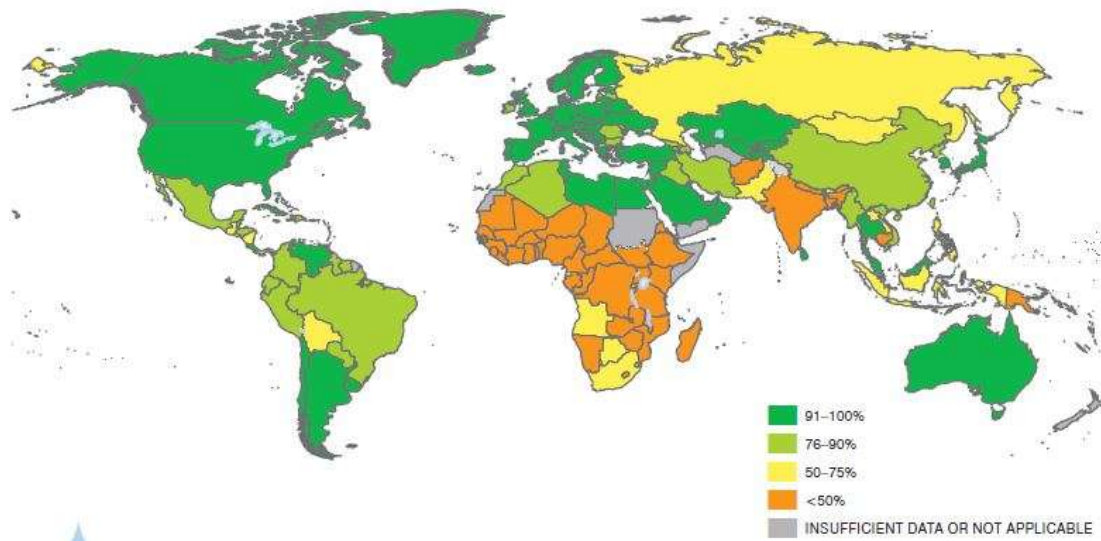
who did not have access to improved water are in rural areas, where only 51% had access to improved sanitation (Joint Monitoring Program, 2015a).

Countries in which less than 50% of the population uses improved drinking water sources are all located in sub-Saharan Africa and Oceania



**Figure 1** Proportion of the population using improved drinking water sources in 2015. Source: Joint Monitoring Programme, 2015a.

In 47 countries, areas or territories, less than half the population uses improved sanitation in 2015



**Figure 2** Proportion of the population using improved sanitation facilities in 2015. Source: Joint Monitoring Programme, 2015a.

In 2010, the UN General Assembly and the UN Human Rights Council recognized water and sanitation as a human right (United Nations General Assembly, 2010a, 2010b). These human rights, as described in the respective resolutions of the General Assembly, are met

through the progressive realization of universal access to sufficient, safe, physically accessible and affordable services (United Nations General Assembly, 2010a, 2010b).

**Target 6.1: By 2030, achieve universal and equitable access to safe and affordable drinking water for all**

TARGET LANGUAGE	NORMATIVE INTERPRETATION
By 2030, achieve	
<i>universal</i>	Implies all exposures and settings including households, schools, health facilities, workplaces, and public spaces
<i>and equitable</i>	Implies progressive reduction and elimination of inequalities between population subgroups
<i>access</i>	Implies sufficient water to meet domestic needs is reliably available close to home
<i>to safe</i>	Safe drinking water is free from pathogens and elevated levels of toxic chemicals at all times
<i>and affordable</i>	Payment for services does not present a barrier to access or prevent people meeting other basic human needs
<i>drinking water</i>	Water used for drinking, cooking, food preparation and personal hygiene
<i>for all</i>	Suitable for use by men, women, girls and boys of all ages including people living with disabilities

**Figure 3** Normative interpretation as regard the terms employed in target 6.1. Source: Joint Monitoring Programme, 2017.

**Target 6.2: By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations**

TARGET LANGUAGE	NORMATIVE INTERPRETATION
By 2030, achieve	
<i>access</i>	Implies facilities close to home that can be easily reached and used when needed
<i>to adequate</i>	Implies a system which hygienically separates excreta from human contact as well as safe reuse/treatment of excreta in situ, or safe transport and treatment off-site
<i>and equitable</i>	Implies progressive reduction and elimination of inequalities between population sub-groups
<i>sanitation</i>	Sanitation is the provision of facilities and services for safe management and disposal of human urine and faeces
<i>and hygiene</i>	Hygiene is the conditions and practices that help maintain health and prevent spread of disease including handwashing, menstrual hygiene management and food hygiene
<i>for all</i>	Suitable for use by men, women, girls and boys of all ages including people living with disabilities
<i>end open defecation</i>	Excreta of adults or children are: deposited (directly or after being covered by a layer of earth) in the bush, a field, a beach, or other open area; discharged directly into a drainage channel, river, sea, or other water body; or are wrapped in temporary material and discarded
<i>paying special attention to the needs of women and girls</i>	Implies reducing the burden of water collection and enabling women and girls to manage sanitation and hygiene needs with dignity. Special attention should be given to the needs of women and girls in 'high use' settings such as schools and workplaces, and 'high risk' settings such as health care facilities and detention centres
<i>and those in vulnerable situations</i>	Implies attention to specific WASH needs found in 'special cases' including refugee camps, detention centres, mass gatherings and pilgrimages

**Figure 4** Normative interpretation as regard the terms employed in target 6.2. Source: Joint Monitoring Programme, 2017.

In 2015, the UN General Assembly adopts the 2030 Agenda for Sustainable Development, a plan of action in favour of people, the planet and prosperity, which also intends to strengthen universal peace and access to justice (United Nations General Assembly, 2015). This agenda establishes 17 Sustainable Development Goals<sup>2</sup> (SDGs) and 169 goals designed to be universally relevant and applicable to all countries. The SDGs require an integrated approach with respect to social, economic, and environmental dimensions. As for the MDGs,

<sup>2</sup> More information available at: <http://www.un.org/sustainabledevelopment/es/objetivos-de-desarrollo-sostenible/>

the SDGs integrate a specific objective for water and sanitation (SDG 6), which includes a series of targets that address all aspects of the water and sanitation cycle, while reflecting the recognition of water and sanitation as a human right. *Figures 3 and 4* capture the normative interpretation of Targets 6.1 and 6.2, which refer to water supply and sanitation, respectively.

In terms of monitoring, and in order to report on progress towards Targets 6.1 and 6.2, it was proposed to expand the water and sanitation ladders mentioned above. Among the main differences proposed, a new threshold (or higher "rung") was established for the level of drinking water service and sanitation (called "safely managed"). Additionally, a specific ladder for hygiene (hand washing) was proposed. Thus, the drinking water ladder distinguishes between "safely managed services", "basic services", "unimproved", and "surface water" (without service). Sanitation, on the other hand, is broken down into "safely managed services", "basic services", "limited services" (shared facilities), "unimproved", and "open defecation". Finally, the hygiene ladder reports separately on "basic facilities", "limited" (with water, but without soap), and "without facilities". The underlying idea behind the improvement of service levels is not only to increase the number of people with access, but also to promote progressive improvements in the quality of services, based on the normative criteria of the human right to water and sanitation (availability, quality, accessibility, acceptability, and affordability). Therefore, the indicators used for monitoring have been designed to match the normative interpretation of this right as closely as possible, while recognizing that routinely measuring some elements is not yet possible. It should be emphasized that countries are not expected to copy–paste the global objectives into their own national plans. In this regard, the 2030 Agenda asks countries to set their own national goals guided by world-level ambitions yet still taking into account national circumstances. Global indicators can be used even if national targets aim to reach a certain level, rather than universal coverage, by 2030. In countries where basic services are not yet universal, national objectives may thus focus more on the lower rungs of the water, sanitation, and hygiene ladders (Joint Monitoring Program, 2017).

## 2.2. HONDURAS, LEMPIRA: CONTEXT OF THE CASE STUDY

The Republic of Honduras is located in the centre-north of Central America. It is bordered to the north and east by the Caribbean Sea, to the southeast by Nicaragua, to the south by the Gulf of Fonseca and El Salvador, and to the west by Guatemala. Honduras is divided into 18 departments, and these into 298 municipalities, according to the 2001 Census, with an estimated 3,731 "aldeas" (villages) and 30,591 "caseríos" (hamlets).



**Figure 5** Political map of Honduras<sup>3</sup>.

**Table 1** General information. Source: <http://www.presidencia.gob.hn/index.php/honduras/historia>.

HONDURAS GENERAL INFORMATION	
Official Name	Republic of Honduras
Capital	Tegucigalpa, MDC
Territorial extension	112,492 km <sup>2</sup>
Population	8,630,890 inhab. (2015) [INE]
Population density	75 inhab. / km <sup>2</sup>
Official language	Spanish
Currency	Lempira

The population is mainly engaged in agricultural activities, trade, manufacturing, finance, and services. The territory is very rugged, with high mountains, high plains and deep valleys, which host an enormous biodiversity. Honduras preserves some of the best archaeological remains of the Mayan culture and good examples of the advanced hydraulic engineering of its settlements.

<sup>3</sup> Sources: [www.wikipedia.org](http://www.wikipedia.org); [mapadehonduras.blogspot.com](http://mapadehonduras.blogspot.com)



## **Water and sanitation sector: current situation**

Honduras belongs to the Latin American and Caribbean group according to the assessments carried out by the JMP. It is one of the 16 countries that achieved its goal of increasing access to piped water in premises by more than 25%, and of reducing open defecation by more than 25%, between 1990 and 2015 (Joint Monitoring Program, 2015). The most recent estimates point out that:

- The population with improved drinking water sources in urban areas increased from 92% to 97%;
- The population with improved drinking water sources in rural areas increased from 60% to 84%;
- The population with improved sanitation facilities in urban areas increased from 70% to 83%;
- The population with improved sanitation facilities in rural areas increased from 33% to 78%.

Despite having achieved the targets proposed by the MDGs, there are still significant disparities between the richest and poorest population, especially in rural areas of the country. In addition, a part of the population still spends more than 30 minutes to fetch water, and Honduras continues to be one of the countries in which water collection in rural areas falls mainly on women.

## **Governance**

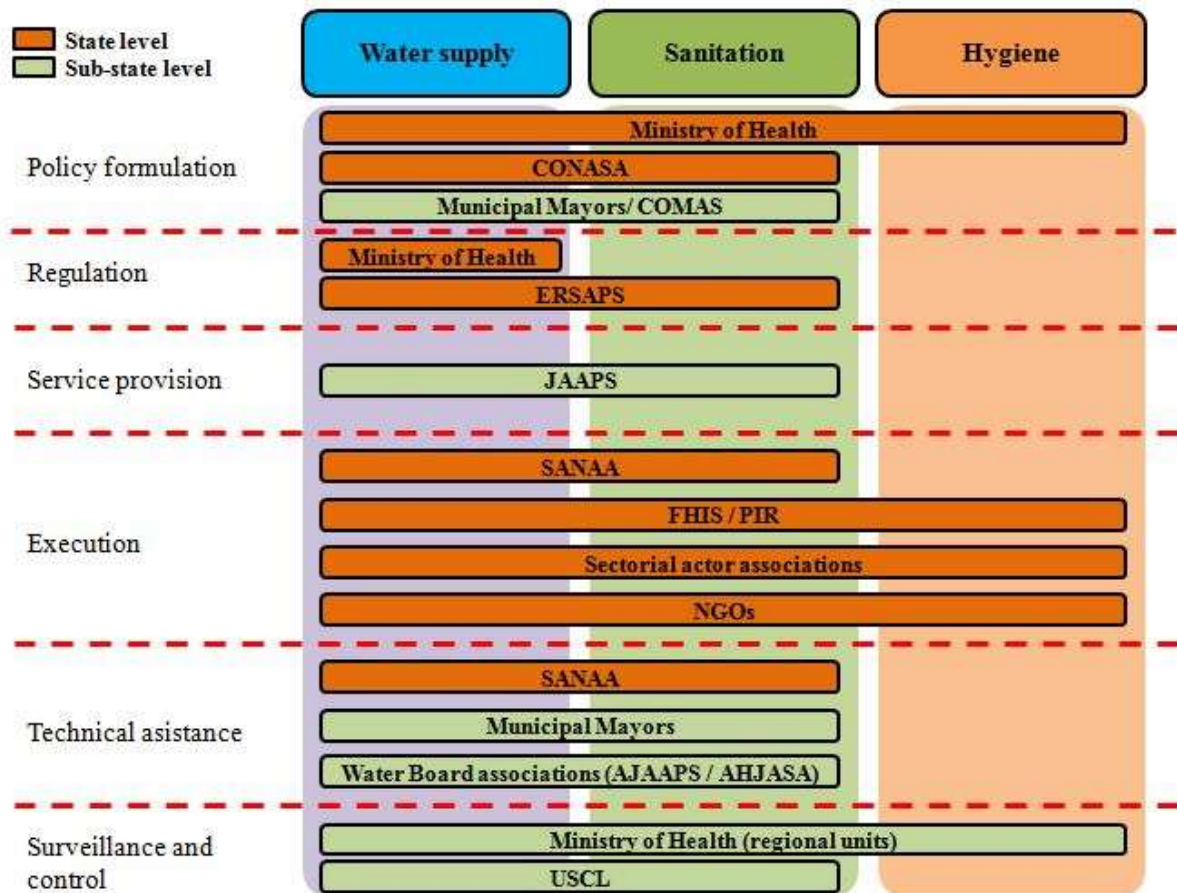
The Drinking Water and Sanitation (APS, by its acronym in Spanish) sector of Honduras is undergoing a process of profound change based on its decentralization policies, which establish the orderly transfer of APS services to the Municipalities.

The Ley Marco (Framework Law), approved in 2003, indicates the need to readjust the legal and institutional framework of the APS sector, in order to improve the planning, regulation, control, and provision of the services. Framed in the State's decentralization policy, the objective is to assign a leading role to the Municipal Governments; as this needs a broader participation of the social sectors, it implies establishing mechanisms to encourage the joint participation of the municipal authority and citizens. In this way, the Ley Marco determines in a precise way the different roles of the actors in the sector. It should be noted that national agents exercise their skills at both rural and urban levels.

At the state level, CONASA (National Council for Drinking Water and Sanitation) represents the governing body. It is mainly responsible for the formulation of policies, the definition of objectives and goals, the development of national strategies and plans, and the elaboration of the investment plan. ERSAPS (Regulatory Entity for Drinking Water and Sanitation Services) regulates the provision of APS services and counts with functional, technical, administrative, and budgetary independence. SANAA (National Autonomous Service of Water Systems and Sewers) fulfils mainly two roles related to the rural water and sanitation sector: 1) as the technical secretary of CONASA, it supports the formulation of policies (guiding functions); and 2) it provides technical assistance and support for the execution of rural programs. Finally, although not specifically mentioned in the 2003 Ley Marco, the Honduran Social Investment Fund (FHIS, by its acronym in Spanish) is worth mentioning due to its presence in the sector, its relevance, and its activities; FHIS is the executing agency of the Government of Honduras, mainly through the Unity Coordinator of the Rural Infrastructure Project (PIR, by its acronym in Spanish). Within the general objective of rural poverty reduction through access to basic infrastructure services, the sub-projects of drinking water and sanitation aim to increase coverage in rural areas, promote sustainability of services, and promote hygiene, benefiting the dispersed rural population that is still not served.

At the sub-state level, the Municipal Water and Sanitation Commissions (COMAS, by its acronym in Spanish) have been created to implement the decentralized supervision and control of APS services. It is noteworthy that COMAS are integrated by community members and councillors of the Municipal Mayors. Its functions focus on applying the regulations within the municipality, based on the laws and guidelines formulated by CONASA. On the other hand, the Local Control and Supervision Units (USCL, by its acronym in Spanish) are integrated by community members with the responsibility of monitoring the compliance of the law and its regulations, depending on a so-called “technician for regulation and control” in every municipality. In other words, it is ERSAPS counterpart, but at the municipal level.

In the rural area, more than 5000 Drinking Water and Sanitation Administration Boards (JAAPS, by its acronym in Spanish) apply community management, framed in the Regulation of Administrative Boards issued by ERSAPS. These JAAPS are responsible for the operation, maintenance, and administration of drinking water services, and they have the power to manage their legal status, establish their statutes, and set and collect fees (ERSAPS, 2006).



**Figure 6** Representation of main actor presented in Honduran water and sanitation sector, institutional and non-institutional, differentiating areas of action and competences. Source: own elaboration, from CONASA, 2013.

Figure 6 schematically integrates the main actors presented above. However, the existence of other agents can be appreciated as well, which also have a relevant role in the Honduran APS sector. In this sense, several aspects to be mentioned. First, and despite the multiplicity of actors present in the sector, communication—in terms of information exchange—has been found to be insufficient. This is a key aspect, since several of the existing actors, such as the Ministry of Health, FHIS / PIR, and NGOs, are generators of information. Second, and in terms of the decision-making processes that occur in the sector, two clearly differentiated groups can be distinguished: 1) institutional actors, on whom a large part of the APS service delivery responsibility falls. These are usually characterized by a limited experience in the sector and a deficiency in the performance of their functions. This fact conditions the existence of decision-making processes that impact the current sectorial situation. Only the FHIS (PIR), which has greater financial support, and the Ministry of Health play an active role and integrate well-defined decision-making processes within it. The work of CONASA in the formulation of municipal policies is also significant, although it recognizes the still broad way to go, especially as a leading institution at the national level; and 2) external co-operators, who are characterized not only by the positive work they do in the APS sector, but also by their incorporation of clearly defined decision-making processes. In this sense, the

need to design strategies that make efficient use of the effort that several relevant actors are developing in Honduras is evident.

### 2.3. RURAL WATER AND SANITATION INFORMATION SYSTEM (SIASAR)

The Rural Water and Sanitation Information System<sup>4</sup> (SIASAR) is a joint initiative, launched in 2011 by the governments of Honduras, Nicaragua, and Panama, whose strategic objective is to have a basic information tool, updated for and with comparisons between the rural water and sanitation services existing in each country. In 2017, 11 countries were already integrated into initiative and had already designated SIASAR as the national reference information system.

The specific objectives of this information system are to: i) support action planning, coordination, and evaluation regarding the different actors in the sector; ii) monitor the coverage, quality, and sustainability of rural APS services; iii) register the performance of technical assistance providers, including their limitations in logistics; and iv) allow the transfer of water and sanitation statistical data, facilitating the exchange with other sectorial databases.

Public investment in the APS sector of Latin America and the Caribbean countries has traditionally been biased towards the construction of new infrastructures, with little attention paid to other factors that affect the sustainability of the provision of APS services (Lockwood et al. al., 2010). Understanding these factors is essential to addressing sustainability gaps and to improving policy development, sectorial planning, priority setting, budget allocation, project design, and technical assistance delivery.

This central idea has led countries to design and agree on a set of monitoring instruments (surveys) to analyze the quality and sustainability of APS services from different perspectives: i) the community; ii) the water system; iii) the service provider; and iv) the technical assistance provider. Additionally, this initiative incorporates combined methodologies and tools to address all aspects related to the collection of information (capture, editing, and validation of data), its processing and analysis, and finally, the use of such information through the web application and generation of reports.

One of the most outstanding aspects of SIASAR is the way in which collected data are organized and analyzed (Pérez-Foguet & Flores-Baquero, 2015). In its so called "conceptual

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<sup>4</sup> More information available at <http://siasar.org/es>



model", six aggregate dimensions are defined to evaluate water and sanitation services from different but complementary points of view. The objective of this structure is to maintain the focus of the different aspects that characterize the increasingly decentralized APS sector. The reason is that, in practice, the roles and responsibilities of sectorial issues are assumed by different actors (Giné-Garriga & Pérez-Foguet 2013a, 2013b).

**Table 2** SIASAR conceptual model: components, dimensions, partial indices, and general index.

Source: Requejo-Castro et al. (2017).

<b>WSP</b> (Water and sanitation performance index)	
<b>NASH (Water, sanitation, and hygiene service level)</b>	<b>ISSA (Water services sustainability index)</b>
<b>Water service level (NSA)</b> Accessibility Continuity Seasonality Quality	<b>Water system infrastructure (EIA)</b> System autonomy Production infrastructure Water catchment area protection Treatment system
<b>Sanitation and hygiene service level (NSS)</b> Sanitation service level Personal hygiene Household hygiene Community hygiene	<b>Service provision (PSE)</b> Organization management Operation & maintenance management Economic management Environmental management
<b>Schools and health centres (ECS)</b> Water supply in schools Water supply in health centres Sanitation and hygiene in schools Sanitation and hygiene in health centres	<b>Technical assistance provision (PAT)</b> Information systems Institutional capacity Community coverage Assistance intensity

The mentioned dimensions propose to measure: i) the Water Service Level (NSA), ii) the Sanitation and Hygiene Service Level (NSH), iii) the service provision in Schools and Health Centres (ECS), iv) the Water System Infrastructure (EIA), v) the Service Provision (PSE), and vi) the Technical Assistance Provision (PAT). Additionally, these dimensions are grouped into two partial indexes: i) Water, Sanitation and Hygiene Service Level (NASH), and ii) Water Services Sustainability Index (ISSA). These partial indexes seek to maintain the focus on aspects related to the quality and sustainability of services, identified by all member countries. Finally, a final level is represented by the Water and Sanitation

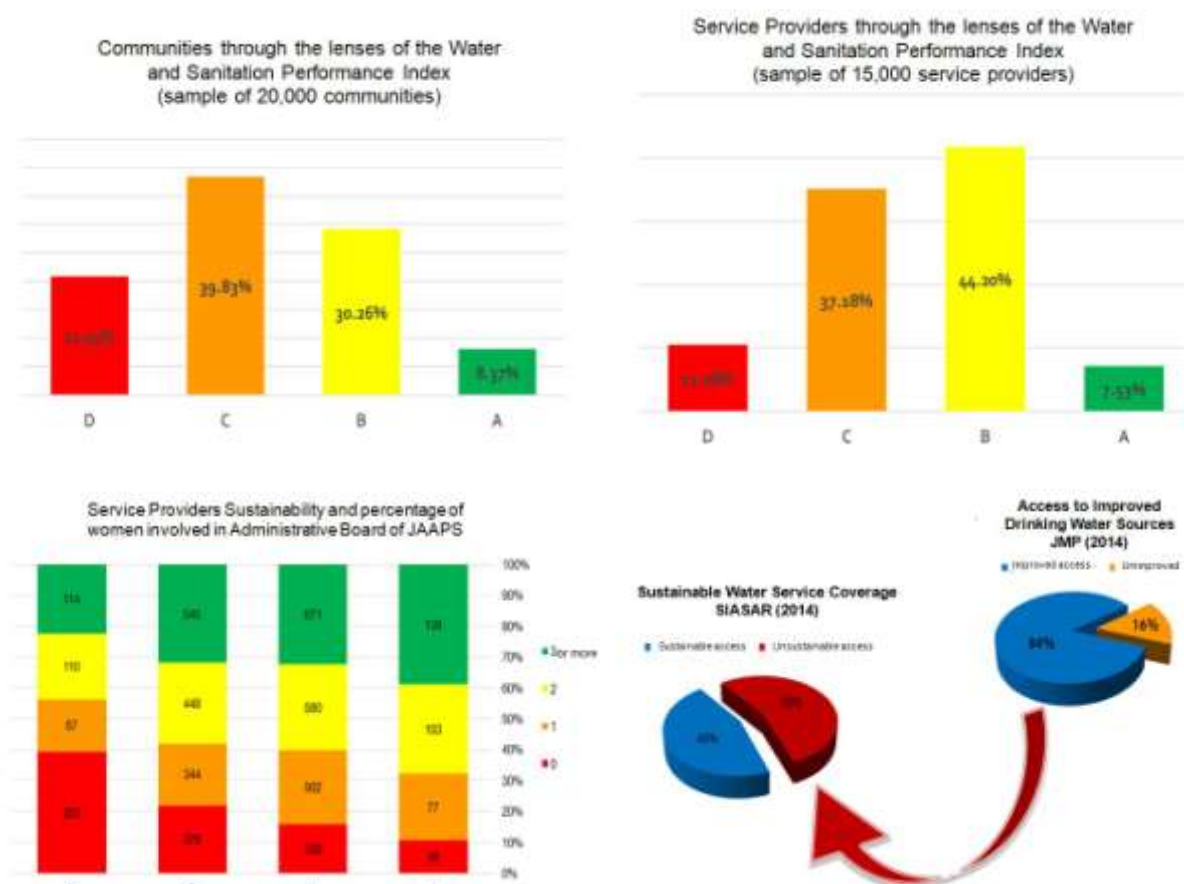
Performance Index (WSP). These latter indices provide a means to initiate discussion and stimulate public interest. These elements are presented in *Table 2*.

Briefly, and as reflected in detail in Requejo-Castro et al. (2017), each dimension comprises four components, and each component is fed by a short list of individual indicators with a total sum of 109. Regarding the methodology used to process the information, first the indicators are classified according to the conceptual model described above. Since the collected data are often represented at different scales (percentage of systems with adequate water treatment, distance to the source in meters, continuity of service in hours per day, etc.), they have to be normalized before the analysis. Thus, a score between 0 and 1 is assigned to each parameter, where 1 represents the best situation and 0, the worst one. Finally, the components are defined by simple and easy-to-use utility functions. The different components of each dimension are then added as a single value. In this sense, it should be mentioned that the final agreement reached by the countries grants the same weight to all components, dimensions, and indices. Additionally, an additive aggregation method is used for the different dimension construction (allows compensation between components) and a geometric aggregation for the definition of partial and general indices. Finally, in order to facilitate prioritization and decision making, obtained results are presented more comprehensible to end users and stakeholders by linking components, dimensions, and indices to a defined set of categories (from A–D, with A being the best result, and D, the worst). These categories are defined according to the following ranges: A [1–0.9], with both limits included, B (0.9–0.7], C (0.7–0.4], and D (0.4–0].

Although the indicators that make up the conceptual model differ to some extent from those proposed to monitor the SDGs, it should be mentioned that the SIASAR initiative admits the need to align with international monitoring systems. In this sense, a thorough review of the questionnaires for data collection is being carried out in order to adapt them to the key monitoring elements of the SDGs (Requejo-Castro et al., 2017).

Considering the above, an example is shown in *Figure 7* of some preliminary results obtained from the information collected in different countries. In this example, the sustainability of APS services in the communities (general index WSP) is only evaluated as such in 8% and 31% of the cases, obtaining a grade of A and B, respectively. It should be noted that reaching a classification of C or a lower implies the need for external help, which is not associated with a sustainable situation. The service providers fared slightly better, with almost 52% of service providers (JAAPS) reaching a grade of A or B in the ISSA partial index. Intriguingly, a high percentage of JAAPS Board of Directors that qualified as A or B were composed of 2 or more women members (of the 7 members required by law): for the A grade, 68% had  $\geq 2$  women, and for the B grade, 60% had  $\geq 2$  women (a lower yet still significant percentage). A final aspect to be highlighted is the difference between SIASAR and the JMP, in terms of access to water. The first has a more restrictive approach, as it

considers other aspects beyond access. As a result, the JMP estimated in 2014 that 16% of the population in Honduras did not have access to improved drinking water sources. In contrast, the SIASAR estimations focused on access to sustainable services and increased this number to 55% of the rural population.



**Figure 7** Preliminary results based on SIASAR information. Sources: World Bank, 2017; SIASAR 2014; JMP 2014.

At the present, and after 6 years participating in the SIASAR initiative, Honduras has exhaustive information on its 3,869 communities (55% of the total estimated rural communities), 3,123 associated water systems, and 2,585 JAAPS (service providers). These numbers reveal one of the most important challenges facing by SIASAR countries. Undoubtedly, information collection is a crucial stage, and it is associated with the need for important human and logistic resources. The challenged faced with this is not only obtaining the information but also keeping it updated.

In the particular case of Lempira Department, work is being done on as to define the Annual Operational Plan (POA, by its acronym in Spanish) for the year 2017. The objective is to analyze the results of 2016 in order to define the actions to be executed during 2017. Thus,

the definition of strategies for strengthening effectiveness in decision-making processes is based on the information obtained through SIASAR.

As a more specific example, the municipality of Piraera, in Lempira, is immersed in the management of a participatory process among different actors (municipal mayor, civil society, and JAAPS) with the aim to develop a water and sanitation diagnosis and analysis. This context seems auspicious for exploiting SIASAR as a tool to support decision-making and to develop a municipal strategic plan for water and sanitation. This objective, although simplified, will be the central part of this case study.

## 2.4. STATISTICS AS A TOOL FOR DATA ANALYSIS

In order to monitor the compliance with the SDGs, there has been a need to define indicators that measure progress or setback in the achievement of the proposed goals. Information management is of great importance for decision-making, since it allows undesirable situations and trends to be identified, with the aim of ultimately being able to establish measures against them.

Working with large volumes of data requires the use of statistical tools as to develop objective and affordable analysis and, ultimately, to use the information and results to facilitate and support decision-making processes. Specifically, in this case study, the use of software R is proposed, which is an open-access, integrated development environment (IDE).

The information that will be used as a reference comes from a database of 412 communities belonging to the Department of Lempira (Honduras). As mentioned previously, this information is collected in field through SIASAR questionnaires. From these communities, and with the aim to simplify the proposed activities, we will work with 19 indicators<sup>5</sup> (original variables) related to community characteristics, as well as water and sanitation service levels and service provider performance associated with them.

It is essential to recognize that working with large volumes of data, and especially those obtained through questionnaires or surveys, requires information pre-processing in order to make the content easily accessible and manageable. In particular, incomplete or inconsistent data must be either corrected (by elimination of duplicates, anomalies, and atypical data) or recovered in a more complete form.

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<sup>5</sup> Chosen information is an extract of the database available at <http://doi.org/10.5281/zenodo.571351>

In this case study, facilitated data is already pre-processed. This includes the elimination of communities with variables that take NA values ("no answer"), zeros that do not correspond, or errors in the values. For example, answers which specified more than 24 hours of service per day were eliminated. As a result, the number of communities initially selected was reduced from 412 to 386, comprising 22 of the 28 Municipalities of Lempira. This can be considered as a representative sample of the Department of Lempira.

In particular, in this case study, aspects related to basic univariate statistics will be addressed, such as:

- Calculation of typical descriptors in quantitative variables (mean, coefficient of variation, median, quartiles, minimum, and maximums, Fisher's asymmetry coefficient, and Shapiro-Wilk and Pearson Chi-square normality test);
- Construction of simple indicators, based on basic operations between available variables, providing them with interpretative content;
- Transformation and normalization of variables. These techniques will be used to facilitate interpretations and applications of subsequent methods.

Additionally, multivariate statistic concepts will be addressed, such as:

- Calculation of correlation and covariance matrices;
- Principal Component Analysis (PCA), which is a technique used to reduce the dimensionality of a data set. Specifically, a set of observations of possibly correlated variables is converted into a set of observations (new variables) that are not correlated with each other, called principal components<sup>6</sup>. This is achieved by diagonalizing the correlation or the covariance matrix;
- Application of an orthogonal rotation (Varimax) to redistribute variances in a subspace determined by a part of the principal components. Thus, rotated components, called factors by the application of factorial analysis technique, depend strongly on a minimum number of original variables<sup>7</sup>;

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<sup>6</sup> Additional information can be found in Maindonald and Braun (2010) - Chapters from 2 to 4, and 12 -, Kottegoda and Rosso (2009) - Chapters 1, 5 and 6 -, Ross (2014) - Chapters 2, 7 and 8, Ugarte et al. (2015) - Chapters 2 and from 7 to 10.

<sup>7</sup> More information related to rotations and their geometric interpretation in Tucker and MacCallum (1997) - Chapters 8 and 9 -, Kottegoda and Rosso (2009) - Chapter 7 -. Additional information regarding index construction, variable selection and weighting methods can be found in Nardo et al. (2005) - Chapter 2 -.

- Multiple Linear Regression (MLR), used to approximate a dependent variable based on some predictor variables values<sup>8</sup>;
- Definition of indexes related to variance (unsupervised techniques) and based on supplied information (supervised techniques).

### 3. CLASS ACTIVITY

This activity is structured in two large blocks:

**Block I.** The work in Block I should be carried out in small groups (of 3 or 4 people), to encourage a final sharing. The duration of this activity is estimated to be 1 hour, with 30 minutes of group discussion, and 30 minutes of general discussion. We suggest that the professor acts as a moderator. In order to facilitate the development of this block and the subsequent activities, we recommend that the students receive all information presented in Section 2 of this case study. Ideally, the contextualization of the case study should be facilitated prior to developing the activities, in order to provide adequate time for reading and understanding.

**Block II.** This is a guided workshop by the teacher. Thus, we recommend that the students work individually. We estimate that Block II should take 2 hours; note that it can be carried out in one or two sessions, at the discretion of the teacher. Specifically, the workshop consists of observing and replicating step-by-step the provided programming code. Once the code has been replicated, with each step understood and each result interpreted, a group discussion should be carried out on the context and data availability, and their implications in planning and decision making.

For workshop implementation, a guide composed of 4 parts is provided, each with a different objective. All necessary material is provided in form of Annexes and under the following nomenclature:

- A.I\_Caso\_Estudio\_G.pdf → R procedure guide.
- A.II\_CE\_guiado.R → R procedure code.

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<sup>8</sup> More information regarding regression models can be consulted in Kottegoda and Rosso (2009) - Chapter 6 -, Maindonald and Braun (2010) - Chapters from 5 to 7 -, Ross (2014) - Chapters 9 and 10, Ugarte et al. (2015) - Chapter 12 -.

- A.V\_datos\_CS.RData → Initial data by communities.
- A.VI\_WSP\_CS.RData → Additional data of numerical assessment (for Part II).

## BLOCK I

This first activity aims to raise awareness of the importance of access to adequate water and sanitation services. At the same time, it also seeks to highlight the relevance of monitoring water and sanitation progress to support decision-making processes (together with the difficulties involved). In this sense, and after presenting the theoretical content of this case study, we propose to reflect on and then answer the following questions:

1. Which are the direct and indirect impacts for the various aspects of water and sanitation progress? For this, we propose that the students fill out the following table, indicating the direct and indirect impacts associated with the specific aspects; however, students can also add further aspects. Impacts can be identified from distinct perspectives, such as health, development, or environment, among others.

ASPECT (deprivation)	DIRECT IMPACTS	INDIRECT IMPACTS
<b>Water quality</b> (presence of pollutants)		
<b>Availability</b> (service hours per day)		
<b>Affordability</b> (water tariff paid)		
<b>Water accessibility</b> (coverage)		
<b>Sanitation accessibility</b> (coverage)		
<b>Gender equality</b> (women presence in Administrative Boards)		

2. Which positive and negative aspects may exist in the development of global monitoring systems? And in the alignment of other information systems with these global initiatives (e.g. SIASAR)?

3. Considering the specific context of Honduras, it is clear that obtaining information is one of the most important challenges in the sector. What initiatives could be proposed to facilitate this task?
4. The policy of decentralization of APS services in Honduras is transferring responsibility for service provision and management to the municipalities, where it is taken on by civil society groups that are usually inadequately prepared. How could this transition be made more favourable?

## **BLOCK II**

The objective of this block is to introduce the students to basic guidelines that permit an autonomous use of the proposed software. In parallel, it should lead to a discussion about the interpretation of the obtained results, specified to the context of Lempira Department (Honduras).

### **Part 0**

1. Based on available variables, construct simple indicators (minimum 6) that allow community water and sanitation situations to be assessed;
2. Apply a basic descriptive analysis that allows the behaviour of each indicator to be characterized, reflecting on the need to transform and / or normalize them;
3. Apply a descriptive analysis—this time multivariate—that allows possible relationships between indicators to be identified, using graphs and correlation matrices;
4. Save the database with the constructed indicators in order to use it in the subsequent activity.

### **Part I**

1. Carry out PCA. Decide the number of components to work with and identify significant indicators;
2. Construct variance-based indices according to the direction of the principal components. Approximate the total variance by grouping the components.



## Part II

1. From the Water and Sanitation Performance (WSP) numerical valuation available (A.VI\_WSP\_CS.RData), apply MLR successively to identify the most influential indicators on WSP;
2. Construct an index based on the generated linear model.

## Part III

Base on your previous work, answer the following questions:

1. Which are the indicators (variables) that have the most influence when applying PCA? And when applying MLR? Are they the same? To answer these questions, use the table of alpha coefficients;
2. Is there any relationship between the constructed indexes (I1, I2, IMV, IWSP)? It is recommended to use the dot charts as support;
3. What would be the impact of a reduction of variables, both on practice and in terms of data collection?
4. Which communities should be worked with first? Which criteria would be more convenient to use: constructed indexes, which try to focus on the "relevant" variables, or only coverage aspects? In order to justify the answer, it is suggested to generate rankings that allow the worst-evaluated communities to be visualized.

### 3.1. SOLUTION AND EVALUATION CRITERIA

#### Block I solution

Taking into account that the answer possibilities are open, we have listed some possibilities in the Table below to order to guide the teacher/moderator during the general debate.

1. Which are the direct and indirect impacts for the various aspects of water and sanitation progress? (using the following table).

ASPECT (deprivation)	DIRECT IMPACT	INDIRECT IMPACT
<b>Water quality</b> (presence of pollutants)	<ul style="list-style-type: none"> <li>- Human health affected (including death)</li> <li>- Ecosystem deterioration (pollution)</li> </ul>	<ul style="list-style-type: none"> <li>- Difficulty to develop capacities (poverty increment); health expenditure increases</li> <li>- Subsistence resource reduction (food security decreases and poverty increases)</li> </ul>
<b>Availability</b> (service hours per day)	<ul style="list-style-type: none"> <li>- Needs cannot be met when required (drinking and cooking, hygiene, washing food and clothes)</li> </ul>	<ul style="list-style-type: none"> <li>- Economic investment, for example, in household deposits for water storage</li> </ul>
<b>Affordability</b> (water tariff paid)	<ul style="list-style-type: none"> <li>- Discrimination against the most unfavourable sectors of the population</li> <li>- Possible generation of social conflicts</li> </ul>	<ul style="list-style-type: none"> <li>- Difficulty in accessing to other services; Increment of the gap between those who have more and those who have less</li> <li>- Increment of the gap with public institutions or actors responsible for service management; Citizen participation decrement</li> </ul>
<b>Water accessibility</b> (coverage)	<ul style="list-style-type: none"> <li>- Water consumption needs cannot be guaranteed, in case the source is far away (drinking and cooking, hygiene, washing food and clothes)</li> <li>- Insecurity increment (especially when women and girls collect water and when distances are wide)</li> </ul>	<ul style="list-style-type: none"> <li>- Difficulty to develop vital and economic activities</li> <li>- Potential increment of aggressions against girls and women</li> </ul>
<b>Sanitation accessibility</b> (coverage)	<ul style="list-style-type: none"> <li>- Human health affectation</li> <li>- Common environment deterioration (habitat)</li> </ul>	<ul style="list-style-type: none"> <li>- Difficulty to develop capacities (poverty increment); Health expenditure increment ; Lack of awareness about hygienic practices</li> <li>- Proliferation of parasitic diseases and infectious pathogens; Loss of eco-tourism value (economic impact)</li> </ul>
<b>Gender Equality</b> (women presence in Administrative Boards)	<ul style="list-style-type: none"> <li>- Discrimination against women in decision-making</li> <li>- Empowerment possibilities decrement</li> </ul>	<ul style="list-style-type: none"> <li>- Promotion of patriarchy and women dependency</li> <li>- Gender inequality continuity</li> </ul>

**2.** Which positive and negative aspects may exist in the development of global monitoring systems? And in the alignment of other information systems with these global initiatives (e.g. SIASAR)?

A first positive aspect that could be highlighted would be using common indicators for the comparison of global data, as having countries "speak the same language" allows those countries or regions that require more attention to be identified. Second, the establishment of international goals has been a precursor of national policies and strategies with the aim of improving the sectorial situation. Third, and related to the first point, the visualization of sector status is relevant, both to encourage the initiative of the countries to improve and to stimulate international cooperation.

Negative aspects could include the difficulty to obtain and update the proposed information for some countries. The definition of "simple" indicators may leave out other relevant aspects that favour the identification of those sectors of the population that are most vulnerable. However, it must be recognized that obtaining more detailed information implies a cost increment, which would even further hinder the information-gathering capacity of some countries.

The alignment of other monitoring systems is relevant for contributing to international goals monitoring. Undoubtedly, the possibility of obtaining information compatible with the proposal at an international level would favour a more accurate and reliable monitoring. Data of this type are the central axis of any information system that would stimulate the positive aspects mentioned above. However, other information systems may have specific interests, which are different than the ones contemplate globally. Such considerations should not represent a problem, nor should it limit other national interests and goals.

**3.** Considering the specific context of Honduras, it is clear that obtaining information is one of the most important challenges in the sector. What initiatives could be proposed to facilitate this task?

As explained above, there is a multiplicity of actors, some of whom are generators of information. Basically, this is possible thanks to the availability of human and logistical resources, aspects which other actors do not have. At the same time, the existing deficiency in the exchange of information has become relevant. Therefore, the creation of a common information system that integrates a series of agreed indicators of interest could be a first step to be taken. It should be an information system accessible by any user. Thus, the common information could be obtained in the field by the different existing actors. In this sense, the important costs associated with this task could be shared collaboratively and within the possibilities of each actor.

4. The policy of decentralization of APS services in Honduras is transferring responsibility for service provision and management to the municipalities, where it is taken on by civil society groups that are usually inadequately prepared. How could this transition be made more favourable?

One of the first aspects to take into account is the preparation or capacity of the actors present in the municipalities, which is usually quite low. Thus, a first approach might be to training local agents. However, this would not be enough if local public institutions were not also trained. The main objective is to improve the involvement of these institutions in the regulation, supervision, and support of service management. Due to the fact that training is a gradual process, technical assistance by professionals during a certain period of time would be necessary. At the same time, mechanisms of citizen participation and accountability should be established, in order to promote awareness about water and sanitation as well as transparency. Another interesting initiative would be designating/creating spaces for discussion and debate, in which others' experiences can be shared and learnt from.

## **Block II solution**

The numerical solution of the proposed activity, including the discussion of results, can be found in the attached document, under the name "Caso\_Estudio\_G.pdf". It should be mentioned that this is not the only solution, as students can construct their own indicators or define different criteria from those proposed.

In any case, for both PCA and MLR, 3 of the 7 variables are discarded. This implies a significant reduction in terms of time and costs, if the considered variables do not intervene with data collection. However, and despite the fact that both methods recognize the same 4 variables as relevant (coverage indicators and ratios), the relative importance of these variables is different for each method. Therefore, and depending on information available (data and / or qualitative assessment), the most important aspects or variables to be considered might differ. From a planning perspective, communities in more deficient situations can be identified according to a new index proposal (IMV and IWSP), which incorporates more information to typical coverage assessments. In an extended manner, and over many years, investment decisions in the water and sanitation sector have been made based on the percentage of coverage, leaving out important aspects of the service provider and the quality of the service itself.

## **Evaluation criteria**

In order to provide the students with an objective and transparent evaluation system, we suggest using the provided rubric (see Annex IX), which shows: i) the knowledge that

students are expected to acquire, and ii) the criteria that will be used to evaluate the content of the resolution associated with the proposed activities.

The way to use the rubric depends on the previous knowledge by the students and professors. That is, the rubric must be provided with the information related to the contents to be evaluated. Thus, some guidance should be given to students to allow them to carry out the proposed activities.

Specifically, to evaluate Block I, each group must submit a written document answering the questions raised. These answers will be evaluated based on the proposed rubric. However, the professor is free to choose an alternative evaluation method if she/he considers it more appropriate.

Block II will not be evaluated, as it is a guided workshop with the sole objective of providing the necessary knowledge to develop the autonomous activity that is proposed.

#### 4. HOMEWORK ACTIVITY

In this activity, students are suggested to work in small groups of 3 or 4 (note that maintaining the same working groups as in the previous activity would make it easier to evaluate the overall work). This activity can take about 8 or 10 hours. Basically, it consists of applying the methodology shown in the guided workshop, with the difficulty of incorporating into the analysis a G1 and G2 classification of the communities, forcing a double-blind analysis to be carried out independently.

The proposed activity integrates the generation of code and interpretation of results simultaneously. In this sense, the wording provided in this section will facilitate the development of the activity in an orderly manner, through different suggestions and questions. The necessary material is provided in the form of Annexes and under the following nomenclature:

- A.VII\_IND\_CS.RData<sup>9</sup> → Initial data, simple indicators constructed during the class activity.
- A.VIII\_CLAS\_G12\_CS.RData → Data of communities graded as G1 or G2.

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<sup>9</sup> It should be mentioned that this database is provided within the Annexes. However, it is recommended the students to create their own database during the guided workshop. In so doing, the character “#” should be eliminated from the code line: `save(data_f,file="IND_CS_nombre.RData")`.

- A.VI\_WSP\_CS.RData → Additional data of numerical assessment (for Part II).

This activity requires the students to work autonomously with the proposed statistical software, analysing and interpreting the results obtained for this case study. For this purpose, we recommend to follow the guidelines detailed below in an orderly manner, as well as to answer the proposed questions:

## Part 0

1. Load saved data from guided workshop (A.VII\_INS\_CS.RData), which corresponds to the simple indicators constructed, transformed, and normalized for the 386 communities at hand;
2. Load data associated to the classification G1-G2 (A.VIII\_CLAS\_G12\_CS.RData) of the communities and incorporate this grading as an additional column in previously loaded database (community identifier, 6 simple indicators, and classification G1-G2). How many communities of each class exist? Identify the differences that characterize each group, in terms of indicators. Use dot charts and different colours depending on the class;
3. Apply the summary function constructed in the previous activity for G1 and G2 communities separately. What does the summary show? Is it possible to conclude that G1 communities have a higher value than G2 communities? Draw histograms and box plots for all variables and for each class. Analyze and discuss, taking previous activity as an example;
4. Use point graphs crossing some of the variables. Is there any relationship among these variables? Calculate the covariance matrices by group and discuss the results. How could the covariance matrix be interpreted? Which variables are more related to each other (in each group)? Is it similar to what was observed in the previous activity (guided workshop)?

## Part I

1. Apply PCA to G1 class communities. Explain what this method is about. Could it be applied without using the default function of R? How?
2. Construct indices according to selected principal components and an index that approximates the total variance. How many components should be used? Which percentage of the variance explains each selected component? Which is the main

difference between the indices related to each principal component and the total variance index? Which are the most significant indicators (dimensionality reduction)?

3. Repeat the procedures for G2 class communities.

## Part II

1. Incorporate WSP numerical valuation into the database at hand.
2. Apply a linear regression to G1 class communities, considering the 7 indicators. Are outliers identified? If yes, eliminate such data. Does the linear regression improve by eliminating these data?
3. Apply successive linear regressions eliminating indicators until the best model is adjusted. Is it obtained a reasonable  $R^2$ ? Do any of the models correctly represent the WSP index? Reflect on the amount of data available. How many and which indicators are finally significant?
4. Construct a new index from the chosen linear model, in case a valid model is achieved;
5. Repeat the previous procedure for the G2 class communities.

## Part III

Answer the following questions based on the results obtained. For this purpose, we recommend to use the graphics and tables constructed during the development of the activity:

1. Which are the indicators (variables) that are the most influential when applying PCA and MLR? Are they the same, or do they coincide? Use alphas coefficients table. Is there any relationship among the indices constructed by class? Use point graphics as support;
2. What additional information about the groups is obtained by applying the methodology separately? Can G1 be differentiated from G2 according to the variables that are the most influential? Is it useful to differentiate communities in G1 and G2 in order to apply investment decision criteria such as those proposed in the guided workshop?

3. In which communities should a hypothetical investment be prioritized, in the case that not all of them can be attended to? Make a proposal (technique) to support this decision. In the proposal, would it be important to consider other factors to support decision-making, such as the existing population in each community?

#### 4.1. SOLUTION AND EVALUATION CRITERIA

##### **Proposed activity solution**

The numerical solution of this homework activity can be found in attached Annexes under the name “A.III\_Caso\_Estudio\_A.pdf” (in addition to “A.II\_CE\_guiado.R”, which corresponds to the solution code). In this occasion, the objective is to guide the teacher in relation to the expected results. It is worth mentioning that the solution corresponds to the numerical values and the graphics obtained when applying the requested methods. However, for this solution, it is useful when the community service levels are classified, which allows the analysis to be focused on those communities with a more deficient situation (in this case, G2). Thus, the analysis is more specific, showing the deficiencies within the group rather than in the entire data set. This directs the focus of proposed investment prioritization, and the associated actions, to those of class G2 (with smaller average of indicator values). In addition, we suggest considering factors such as community population, to invest in those communities in which there is a large population with a low level of service, and the number of women participating in Administrative Boards, to promote gender equality as a catalyst for development within the communities.

##### **Evaluation criteria**

In order to evaluate this activity, a report will be requested that stems entirely from the proposed activity. This report should be accompanied by the codes developed (in the form of annexes). Synthesis capacity should be evaluated, based on the simulation of using the report as a guide for the administration of Lempira in its decision-making processes.

We suggest using the rubric (as mentioned previously) for the report evaluation (see Annex IX). Specifically, those technical aspects identified in the rubric will be evaluated. However, and depending on students’ responses, evaluation might also consider reference made to other aspects not included in the rubric. Therefore, the rubric represents a possible instrument to facilitate the evaluation of the proposed activities as a whole. As previously mentioned, the teacher is free to choose an alternative evaluation method if he/she considers it more appropriate.



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## ANNEXES

- I. Class activity procedure guide < A.I\_Case\_Study\_G.pdf >
- II. Class activity R code (comments in Spanish) < A.II\_CS\_guided.R >
- III. Homework activity solution <A.III\_Case\_Study\_A.pdf >
- IV. Homework activity R code (comments in Spanish) < A.IV\_CS\_autonomous.R >
- V. Class activity data < A.V\_datos\_CS.RData >
- VI. Activities data < A.VI\_WSP\_CS.RData >
- VII. Homework activity data < A.VII\_INS\_CS.RData >
- VIII. Homework activity data (separated by group) < A.VIII\_CLAS\_G12\_CS.RData >
- IX. Evaluation rubric proposal < A.IX\_Evaluation\_rubric.pdf >



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## ANNEX

### Rubric proposal to evaluate the transversal competence of "Sustainability and Social Commitment"

**Definition:** The generic competence of sustainability and social commitment is i) the ability to know and understand the complexity of the economic and social phenomena typical of the welfare society, ii) the ability to relate well-being to globalization and sustainability, and iii) the ability to use technique, technology, economy in a balanced and compatible way.

 **Level 1: Analyze** systematically and critically the global situation, addressing sustainability in an **interdisciplinary manner** as well as sustainable human development, and recognize the social and environmental implications of professional activities in the same field.

 **Level 2:** Apply sustainability criteria and deontological codes of the profession in the **design and evaluation of technological solutions**.

 **Level 3:** Take into account the social, economic and environmental dimensions when **applying solutions and carry out projects** coherent with human development and sustainability.

**Sustainable Development:** *"that one which meets the needs of the present without compromising the ability of future generations to meet their own needs"*. World Commission on Environment and Development (WCED). 1987. *Our Common Future (Brundtland Report)*. United Nations.

**IMPORTANT:** This rubric is of a general character and aims to offer framework criteria to take into account. Therefore, and depending on the activity that will be implemented and evaluated, it is recommended to make the relevant adaptations to provide clarity to the students in relation to the aspects that will be considered in the evaluation.

**Analyze** systematically and critically the global situation, addressing sustainability in an **interdisciplinary manner** as well as sustainable human development, and recognize the social and environmental implications of professional activities in the same field

LEVEL 1	4	3	2	1
<b>Sustainability: Environmental aspects</b>	<b>REFLECTS</b> from the <b>environmental, technological and temporal</b> point of view  <b>IDENTIFYING</b> the technical needs (evaluating them <b>environmentally</b> )  AND <b>DESCRIBING</b> the direct and indirect <b>environmental</b> impacts of the decisions	<b>REFLECTS</b> from the <b>environmental, technological and temporal</b> point of view  <b>DESCRIBING</b> the direct and indirect <b>environmental</b> impacts of the decisions	<b>REFLECTS</b> from the <b>environmental and technological</b> point of view  <b>IDENTIFYING</b> the technical needs (evaluating them <b>environmentally</b> )	<b>REFLECTS</b> from the <b>environmental</b> point of view
<b>Sustainability: Social aspects</b>	<b>REFLECTS</b> from the <b>social, technological and temporal</b> point of view  <b>IDENTIFYING</b> the technical needs (evaluating them <b>socially</b> )  AND <b>DESCRIBING</b> the direct and indirect <b>social impacts of decisions, and integrating the gender perspective</b>	<b>REFLECTS</b> from the <b>social, technological and temporal</b> point of view  <b>DESCRIBING</b> the direct and indirect <b>social impacts of decisions, and integrating the gender perspective</b>	<b>REFLECTS</b> from the <b>social and technological</b> point of view  <b>IDENTIFYING</b> the technical needs (evaluating them <b>socially</b> )	<b>REFLECTS</b> from the <b>social</b> point of view
<b>Sustainability: Economical aspects</b>	<b>REFLECTS</b> from the <b>economical, technological and temporal</b> point of view  <b>IDENTIFYING</b> the technical needs (evaluating them <b>economically</b> )  AND <b>DESCRIBING</b> the direct and indirect <b>economical</b> impacts of the decisions	<b>REFLECTS</b> from the <b>economical, technological and temporal</b> point of view  <b>DESCRIBING</b> the direct and indirect <b>economical</b> impacts of the decisions	<b>REFLECTS</b> from the <b>economical and technological</b> point of view  <b>IDENTIFYING</b> the technical needs (evaluating them <b>economically</b> )	<b>REFLECTS</b> from the <b>economical</b> point of view
<b>Social Commitment</b>	<b>[3] +</b>  AND <b>DESCRIBING</b> <b>links with geographically remote societies</b>	<b>[2] +</b>  AND <b>PRESENTING</b> <b>historical and political arguments</b> to explain them	<b>REFLECTS</b> from the <b>ethical</b> point of view  <b>IDENTIFYING</b> social, economic, environmental, technological, geographical <b>inequalities</b> , etc.	<b>REFLECTS</b> from the <b>ethical</b> point of view

Apply sustainability criteria and deontological codes of the profession in the <b>design and evaluation of technological solutions</b>				
LEVEL 2	4	3	2	1
<b>Sustainability: Environmental aspects</b>	<b>[3]+</b>  AND <b>PRIORITIZING</b> the <b>alternatives</b> according to these criteria	<b>[2]+</b>  AND <b>DESIGNING</b> the solutions or proposals for improvement based on <b>flow analysis (materials, energy, LCA)</b>	<b>REFLECTS</b> from the <b>environmental, technological and temporal</b> point of view  <b>LINKING</b> <b>professional practice</b> with such reflection	<b>REFLECTS</b> <b>critically</b> from the <b>environmental, technological and temporal</b> point of view
<b>Sustainability: Social aspects</b>		<b>[2]+</b>  AND <b>DESIGNING</b> the solutions or proposals for improvement according to the <b>needs of the most vulnerable groups</b>	<b>REFLECTS</b> from the <b>social, technological and temporal</b> point of view  <b>LINKING</b> <b>professional practice</b> with such reflection	<b>REFLECTS</b> <b>critically</b> from the <b>social, technological and temporal</b> point of view
<b>Sustainability: Economical aspects</b>		<b>[2]+</b>  AND <b>DESIGNING</b> the solutions or proposals for improvement based on the direct and indirect <b>economic impacts</b> of the decisions	<b>REFLECTS</b> from the <b>economical, technological and temporal</b> point of view  <b>LINKING</b> <b>professional practice</b> with such reflection	<b>REFLECTS</b> <b>critically</b> from the <b>economical, technological and temporal</b> point of view
<b>Social Commitment</b>		<b>[2]+</b>  AND <b>DESIGNING</b> the solutions or proposals for improvement based on <b>criteria of sense of belonging, efficiency, impact, etc.</b>	<b>IDENTIFIES</b> the <b>rights and aspirations of individuals and social groups</b>  <b>LINKING</b> <b>professional practice</b> with such reflection	<b>IDENTIFIES</b> the <b>rights and aspirations of individuals and social groups</b>



Take into account the social, economic and environmental dimensions when **applying solutions and carry out projects** coherent with human development and sustainability

LEVEL 3	4	3	2	1
<b>Sustainability</b>	<p>[2] +</p> <p>AND <b>EVALUATING</b> the impact and the direct and indirect social, environmental and economic <b>implications and consequences</b> of the decisions</p>	<p>[2] +</p> <p>AND <b>ANALYZING</b> the impact and the direct and indirect social, environmental and economic <b>implications and consequences</b> of the decisions</p>	<p><b>REFLECTS</b> critically on the professional practice from the ethical, social, environmental, economic, technical and temporal point of view systemically</p> <p><b>INTEGRATING</b> knowledge and information of different nature</p> <p>AND <b>DEVELOPING</b> engineering projects consistent with the promotion of human development and sustainability</p>	<p><b>REFLECTS</b> critically on the professional practice from the ethical, social, environmental, economic, technical and temporal point of view systemically</p> <p><b>INTEGRATING</b> knowledge and information of different nature</p>
<b>Social Commitment</b>	<p>[2] +</p> <p>AND <b>EVALUATING</b> the <b>generation and transfer</b> of technology and knowledge between the parties and with society</p>	<p>[2] +</p> <p>AND <b>ANALYZING</b> the <b>generation and transfer</b> of technology and knowledge between the parties and with society</p>	<p><b>IDENTIFIES</b> the rights and aspirations of individuals and social groups</p> <p><b>DEVELOPING</b> projects that explicitly integrate <b>cooperation mechanisms</b> between parties and / or third parties</p> <p>AND <b>CONSIDERING</b> criteria of sense of belonging, efficiency, impact, etc.</p>	<p><b>IDENTIFIES</b> the rights and aspirations of individuals and social groups</p> <p><b>LINKING</b> professional practice with such reflection</p> <p>AND <b>DEVELOPING</b> projects that explicitly integrate <b>cooperation mechanisms</b> between parties and / or third parties</p>



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