Water supply scenarios of agricultural areas: Environmental performance through Territorial Life Cycle Assessment

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Abstract: This paper aims to assess the conditions under which hydraulic projects can be considered as an efficient option, from an environmental point of view, to secure water supply of agricultural areas using the Territorial Life Cycle Assessment (T-LCA) methodology. Firstly, the environmental performance of three theoretical agricultural land-use planning scenarios are defined: (1) a business-as-usual case without irrigation, (2) irrigation with an Inter-Basin Water Transfer (IBWT) and (3) with an Agricultural Reservoir (AR). These are all assessed by computing the territorial eco-efficiency (i.e. a ratio between the services provided by land planning scenarios and their related environmental impacts). Secondly, Territorial Life Cycle Assessment methodology was used to assess the water-energy-infrastructure nexus between the two hydraulic projects. Results indicate that the eco-efficiencies of the scenarios vary according to the service considered and to the type of land use. For land management or economic functions, the scenario without irrigation can perform better, while hydraulic projects are more eco-efficient for functions related to biomass production. The analysis of the water-energy-infrastructure nexus highlights the trade-offs between the two types of project. On one hand, IBWT allows for the use of a low-stress water resource and less energy, but may require high material consumption. On the other hand, AR uses less material while relying on a more scarce water resource. IBWT performs better than AR if the pipe length is less than 100 km, with a water allocation of 1% (proportion of the infrastructure allocated to the considered agriculture area). This study underlines the importance of considering the territorial context in the environmental assessment of land planning projects in order to support decision-making.

Keywords: Eco-efficiency, Decision making, Life Cycle Assessment, irrigation, Agricultural reservoir, Water transfer

Abreviations:

IBWT: Inter-Bassin Water Transfer

AR: Agricultural Reservoir

WSN: Water Supply Network

OIT: On-field Irrigation Technology

PII: Primary Irrigation Infrastructure

SII: Secondary Irrigation Infrastructure

TII: Tertiary Irrigation Infrastructure

CDO: Controlled Designation of Origin

PGI: Protected Geographical Indication

1. Introduction

Agriculture is essential for humanity to meet its food requirements and employs more than a quarter of the world's population (The World Bank, 2021). However, it generates multiple impacts on the environment. Agricultural practices and soil occupation release between 15% and 24% of global greenhouse gas (GHG) emissions (Vermeulen et al., 2012)**.** On one hand, agriculture is by far the primary consumer of water in the world, reaching 70%-80% of the total consumption in the arid and semi-arid zones (Fereres and Rabanales, 2007), and is one of the main drivers of biodiversity loss, ecosystem destruction and freshwater pollution (Rockström et al., 2020). On the other hand, agriculture faces challenges posed by worldwide issues such as climate change. This global change is expected to induce rises in temperature and atmospheric carbon dioxide (CO_2) concentrations, precipitation changes, more frequent occurrences of pests and diseases and of extreme heat and drought, which in turn should affect crop yields and nutritional quality (Lobell and Gourdji, 2012). Hence, due to the global changes induced by human activity and a growing world population, food security is becoming one of the challenges of the coming century and adaptation solutions must be found (Vermeulen et al., 2012).

Irrigation contributes to increasing agricultural yields in dryland areas and is one of the main adaptation strategies implemented for agriculture in the face of climate change, as it makes it possible to secure production yields in the face of increasing drought and temperature (Mbow et al., 2019). Large-scale planning projects can be implemented to secure the water supply of agricultural territories such as water transfers (Piao et al., 2010) or reservoirs (Gorguner and Kavvas, 2020).

These hydraulic infrastructures have a long lifetime, lasting around 50 years (Raluy et al., 2005b). Therefore an ex ante environmental assessment is required to support local decision-making as well as assist territorial planners for the selection of the least impactful alternative for the environment. Indeed, territorial planners require a help-to-decision tool in order to take decisions without regretting the construction of long-lasting infrastructures that present high economical costs and environmental impacts. This assessment should take into account multiple categories of environmental impacts and a lifecycle perspective to avoid pollution transfers within the water-energy nexus (Sharif et al., 2019). Life Cycle Assessment (LCA) is a well-established and recognized methodology to be applied for quantifying the environmental performance of products and services (ISO, 2006a, 2006b). It is a multi-criteria environmental impact assessment method used to quantify the potential impacts of the life cycles of human activities on ecosystems, mineral and fossil resources as well as on human health.

Several studies have used LCA to compare the environmental impact of a variety of hydraulic structures (Byrne et al., 2017) such as water transfers (Muñoz et al., 2010), reservoirs (Ghimire et al., 2014), groundwater pumping (Pradeleix et al., 2015), water reuse (Maeseele and Roux, 2021) and desalinization plants (Raluy et al., 2005a). However, these studies calculate impacts for a functional unit of 1 m^3 of water delivered to the end-user. The boundaries stop at the water supply gate. Therefore, they do not grasp the entire range of services provided by irrigation, such as the territorial socio-economic benefits resulting from agricultural yield conservation. These limitations are inherent of the LCA framework which is a product oriented method at a microscale and do not allow for the full integration of the territorial context, and multifunctionality (Loiseau et al., 2018). The choice of water source as well as the functional unit for water supply systems have been found to greatly contribute to the variability of the water supply impacts (Hospido et al., 2012). Moreover, the impacts of hydraulic infrastructures vary according to certain physical parameters such as lifetimes or length of the infrastructures, annual quantity of water supplied and energy consumption (Raluy et al., 2005b). Consequently, it is also paramount to consider the variability in the design of the hydraulic infrastructure parameters in order to select a specific land planning of water supply.

These limitations can be overcome by using Territorial LCA (T-LCA), an adaptation of the conventional LCA framework, to assess the performance of a territory at a mesoscale and an associated land planning scenario while considering its multifunctionality (e.g. economic, social or environmental land use functions) (Loiseau et al., 2013). Compared to a conventional LCA, the starting point of territorial LCA is no longer the definition of a main function for the studied systems, but the definition of the boundaries of a territory, and associated planning scenarios. Subsequently, two types of indicators must be quantified for each of these scenarios, i.e. environmental impacts and a set of services provided. These indicators are then used to compute eco-efficiency ratios. These have been defined by (Seppälä et al., 2005) as the ratio between services provided by the territory and its environmental impacts. These ratios can help compare the environmental performances of different agricultural scenarios such as in dairy farms (Iribarren et al., 2011) and vineyard irrigation (Canaj et al., 2021). Eco-efficiency allows for a trade-off to be identified between economy and environment to achieve a certain level in the environmental performance of a society (Huppes and Ishikawa, 2005).

A few studies have presently implemented territorial LCA approaches on agricultural areas to support decision-making in the design of land planning scenarios for example in the French Brittany region (Avadí et al., 2016) and Aube department (Borghino et al., 2021) or in the Walloon region of Belgium (Ding et al., 2020). However, none of them have compared the impacts of planning scenarios that integrate the hydraulic infrastructures.

From an environmental point of view, the main objective of this study is to assess the conditions under which hydraulic projects can be selected as an efficient option for securing the water supply of agricultural areas. This can be performed thanks to territorial LCA methodology. Generic conclusions are drawn from a theoretical case study, located in the South of France. The case study is a theoretical agricultural perimeter of 700 ha (size of a small municipality), where water resources ought to become a challenging issue for agriculture within the coming next decades due to climate change (Giorgi and Lionello, 2008). Three main planning alternatives (described in detail in section 2.1.2) will be compared based on a combination of crops and on the implementation or not of hydraulic infrastructures. The latter rely on the use of surface water resources, distinguishing two types of sources, and their dedicated infrastructure, i.e. a local resource consisting of storm water run-off stored in an Agricultural Reservoir (AR), and an imported resource taken directly from a river through an Inter-Basin Water Transfer (IBWT). These water projects have long lifetimes, and local planners and decision-makers need to identify the “no regret” scenarios. This study also addresses the water-energy-infrastructure nexus, and discusses the design conditions under which hydraulic projects can be considered, from an environmental point of view, as viable options for securing agricultural territories.

2. Material and methods

The general methodology adopted in this study follows the territorial LCA approach, and is described according to the four main LCA stages, i.e. (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) impact assessment, and (iv) results interpretation.

2.1. Goal and scope of the T-LCA study

2.1.1. Sub-objectives of the study

To support the main aim of this research work presented above, the study has been divided into three sub-objectives as described in Table 1.

Table 1 Synthesis of the study’s sub-objective and the proposed approach to achieve them

<table>
<tr><th colspan="2">Study’s sub-objectives for land-use planning at the territorial scale</th><th>Proposed approaches and metrics</th></tr>
<tr><td>Sub-objective 1</td><td>Comparing the environmental performance of three agricultural land-use planning scenarios.</td><td>Comparison of the eco-efficiency between the three scenarios, using aggregated LCA endpoint indicators:
$$\text{Eco-efficiency}_{i,j,k} = \frac{Territorial\ FU_{i,j}}{Impact_{j,k}} \quad (1)$$
• $i = Functional\ Unit$
• $j = LCA\ endpoint\ impacts$
• $k = scenario$</td></tr>
</table>

Sub-objective 2	Diagnosis of scenarios: Identifying trade-offs in the water-energy-infrastructure nexus between the irrigation by IBWT and by AR.	Contribution analysis using LCA **midpoint indicators**
Sub-objective 3	Determining the design parameters for which irrigation by IBWT would be more environmentally performant than for AR	Drawing the tipping lines where a given scenario performs better than another, using aggregated LCA **endpoint indicators** for a given set of design parameters

(1) FU: "Functional Unit"

2.1.2. System boundaries

Figure 1 illustrates the studied systems that provide services to society. It comprises the territorial foreground system and the territorial background system (Loiseau et al., 2013). The first includes all the agricultural activities located within the studied area. According to Nitschelm et al. (2016), a cradle-to-gate perspective is adopted and the impacts induced by the agricultural products once they leave the territorial boundaries are not considered. Nevertheless, all the impacts induced by the use of inputs to produce crops are included. They can be divided into two categories: inputs related to water irrigation and others such as energy, fertilizers or pesticides. The latter are part of the territorial background system since they are all assumed to be imported.

Concerning water inputs, dedicated hydraulic projects comprise three sections, i.e., the Primary Irrigation Infrastructure (PII), the Secondary Irrigation Infrastructure (SII) and the Tertiary Irrigation Infrastructure (TII). PII is the infrastructure implemented for water withdrawal. For the IBWT, the PII has a water pumping station that withdraws surface water and an entirely buried water pipeline whose length depends on the location of the water scarce territory requiring a water supply (IEA, 2016). For the AR, the PII has a water reservoir that can store a given volume of storm-water run-off during the winter (Gorguner and Kavvas, 2020) and a pumping station to supply water to the agricultural perimeter. The Water Supply Network (WSN) represents the SII. The WSN is made of water pipelines that are connected to the PII, i.e. on the AR pumping station or on the IBWT water pipeline. Its goal is to transport water from the PII to the TII, which is located on the agricultural field. The TII represents the On-field Irrigation Technology (OIT). The OIT is either a drip-to-drip or a sprinkler irrigation technology depending on the type of crops growing in the agricultural field. Indeed a drip-to-drip irrigation is applied to perennial crops like grapevines whereas sprinkler irrigation is better adapted to annual crops like wheat or corn.

For the AR, the entire infrastructure is in the territorial foreground system since it is dedicated to the studied agricultural area, whereas all the material and energy used for the construction, operation and maintenance phases are in the territorial background system. IBWT is designed to supply water to an entire region, hence sharing with other agricultural areas, cities or industries (Muñoz et al., 2010).It is therefore part of the background system.

The rehabilitation of the hydraulic infrastructure sites when end-of-life is reached is not considered because their impacts are assumed to be insignificant (Risch et al., 2021).

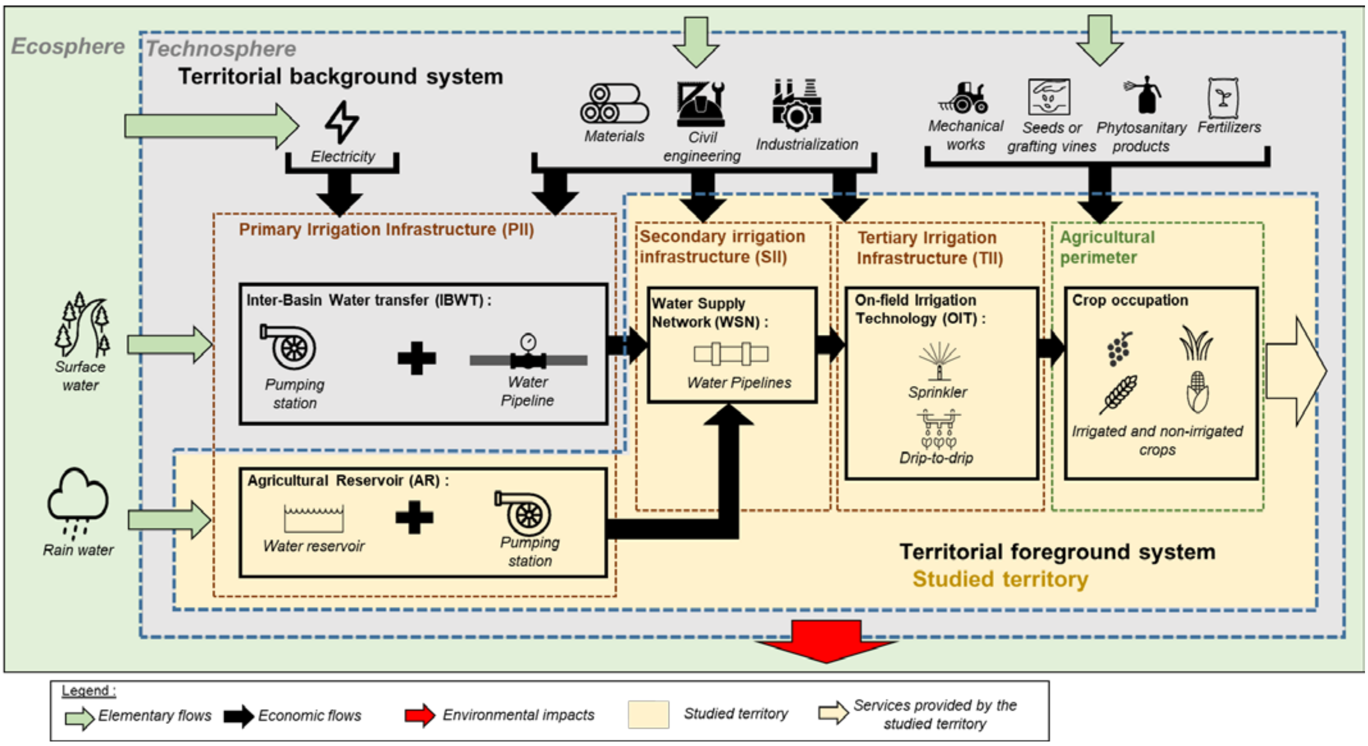


Figure 1 System boundaries of the territorial LCA approach carried out to assess the environmental performance of different agricultural land planning scenarios with or without irrigation infrastructures.

2.1.3. System functions

Territories are multifunctional systems (Loiseau et al., 2013). In general, three main functions can be selected for agricultural systems, i.e. i) economic profit, ii) food production, and iii) land management and occupation (Tendall and Gaillard, 2015). According to Borghino et al. (2021), the total quantity of agricultural products produced annually (Mass of Agricultural Products, MAP in kg), and the total agricultural area harvested annually (Land Occupation – LO in ha of agricultural land) can be employed as proxies to quantify the latter two territorial functions. Finally, the Agricultural Turnover (AT), defined as the sum of annual sales of crop production (in €), is used as a proxy to evaluate the economic profit of the studied territory.

2.1.4. Studied scenarios

Table 2 describes each of the three studied scenarios, which are based on the same size of cultivated area. Since Scenario 0 does not have any irrigation infrastructure, the crops are rain fed. Three types of crops have been selected to be consistent with Mediterranean agriculture and to reflect a diversity of production both in terms of type of plants (perennial or not, cultivated or not), and in terms of valorization (food security or added value creation). The other two land planning scenarios have access to a water supply with IBWT as PII in Scenario 1 whereas Scenario 2 relies on AR. The AR surface of 9.1 ha covers a negligible share of the cultivated area surface, i.e. 1.3%. Therefore, both scenarios have the same SII, TII and agricultural perimeter occupation. Due to irrigation, land occupation in Scenarios 1 and 2 is different from that of Scenario 0. Indeed, non-irrigated crops still occupy the cultivated area while irrigated crops occupy the remaining surface. With access to irrigation, it is assumed that yields could be increased and vines would no longer be registered as Controlled Designation of Origin (CDO) (yield limits) but would rather be classified within Protected Geographical Indications (PGI).

Table 2 Description of the different scenarios of territorial land-use planning

Scenario description	Acronym	**Scenario 0**	**Scenario 1**	**Scenario 2**
		Baseline	**IBWT**	**AR**

<table>
<tr><th></th><th colspan="2">Type of scenario</th><th>No irrigation infrastructure</th><th>Inter-Basin Water Transfer</th><th>Agricultural Reservoir</th></tr>
<tr><td rowspan="3">Infrastructures</td><td colspan="2">Primary Irrigation Infrastructure</td><td rowspan="3">No</td><td>• Pumping station
• Water pipeline</td><td>• Pumping station
• Water reservoir</td></tr>
<tr><td colspan="2">Secondary Irrigation Infrastructure</td><td colspan="2">• WSN : Water pipelines</td></tr>
<tr><td colspan="2">Tertiary Irrigation Infrastructure</td><td colspan="2">• OIT : Sprinkler & drip-to-drip</td></tr>
<tr><td rowspan="7">Agricultural land occupation (ha)</td><td colspan="2">Surface of cultured area</td><td colspan="3">700 ha</td></tr>
<tr><td rowspan="3">Non-irrigated crops</td><td>CDO(1) grapevine</td><td>50%</td><td colspan="2">40%</td></tr>
<tr><td>Fallow</td><td>10%</td><td colspan="2">10%</td></tr>
<tr><td>Wheat</td><td>40%</td><td colspan="2"></td></tr>
<tr><td rowspan="3">Irrigated crops</td><td>PGI(2) grapevine</td><td></td><td colspan="2">10%</td></tr>
<tr><td>Wheat</td><td></td><td colspan="2">30%</td></tr>
<tr><td>Corn</td><td></td><td colspan="2">10%</td></tr>
</table>

(1) CDO : "Controlled Designation of Origin"

(2) PGI : " Protected Geographical Indication"

As mentioned in section 2.1.2, it is noteworthy that, unlike the AR, the IBWT allows for the irrigation of a large area, for which the studied territory only represents a small share. Therefore, only part of the IBWT impact is allocated to Scenario 1. This allocation is calculated by performing the ratio between the annual quantity of water for irrigation needed by the crops and the annual quantity of water circulating in the water pipeline.

2.2. Life Cycle Inventory (LCI)

There are three stages in the inventory phase. Firstly, the different agricultural LCI processes involved in the studied scenarios are collected. Secondly, the hydraulic infrastructures are sized according to an area of 700 ha and their LCI data are gathered. Thirdly, particular attention is paid to water balance and energy consumption calculations for hydraulic infrastructures, based on the crop water needs. This LCA phase is based both on existing LCA databases and studies. Moreover, the co-authors of the paper who are working for French water management companies, i.e. *Société du Canal de*

Provence et d'Aménagement de la Region Provençale and *BRL Ingénierie*, provided detailed design studies of similar hydraulic infrastructures and expert knowledge.

2.2.1. Crop LCI data

Table S. 1 of the Supplementary Information (S.I.) presents the data used for the LCI of the crops considered in this study, i.e. the sources of the inventories and their adaptations for this study as well as the crop yields.

The French agricultural LCA data for corn and wheat were chosen, using the Agribalyse database V3.0. (Koch and Salou, 2020) for the first and World Food LCA DataBase WFLDB 3.5 (Nemecek et al., 2019) for the latter. The use of these two databases limits the risk of inconsistency, since all background processes originate from the Ecoinvent V3 database (Wernet et al., 2016) (e.g. pesticide or fertilizer manufacturing). As no datasets were available with or without irrigation for PGI and CDO grapevines in these two databases, inventories were created using data from French agricultural statistics (Agreste, 2016) and are provided in the S.I.. The quantity of water necessary for the irrigated grapevines originates from a study based in the South of France (IFV and Chambres d'agriculture Languedoc-Roussillon, 2013). The AGEC-LCI (AGricultural Emissions Calculator – LCI) VBA tool was used to calculate the amounts of nitrogen, phosphorus and metals emitted to water, soil and air related to the application of mineral and organic fertilizers as well as on metal-based fungicides (e.g. copper) inputs. Estimation are provided for a variety of annual crops (i.e. sugar beet, durum wheat, soft wheat carrots, rapeseed, alfafa, maize, barley, peas, potatoes, sunflower, triticale) and for one perennial (i.e. grapevine), as well as for temporary grassland and permanent meadow (Santeros et al., 2020). These calculations are based on the assumptions and equations used in the databases providing agricultural LCIs i.e. WFLDB, Ecoinvent and Agribalyse, and are adapted to the French pedoclimatic context. In this study, AGEC-LCI was used for the construction of PGI and CDO grapevines LCIs. In order to be consistent with other Ecoinvent processes all pesticides are assumed to be absorbed by the agricultural ground (Wernet et al., 2016).

2.2.2. Water supply LCI

Figure 2 describes the main design parameters, based on expert knowledge, to be considered for hydraulic infrastructures in Scenarios 1 and 2.

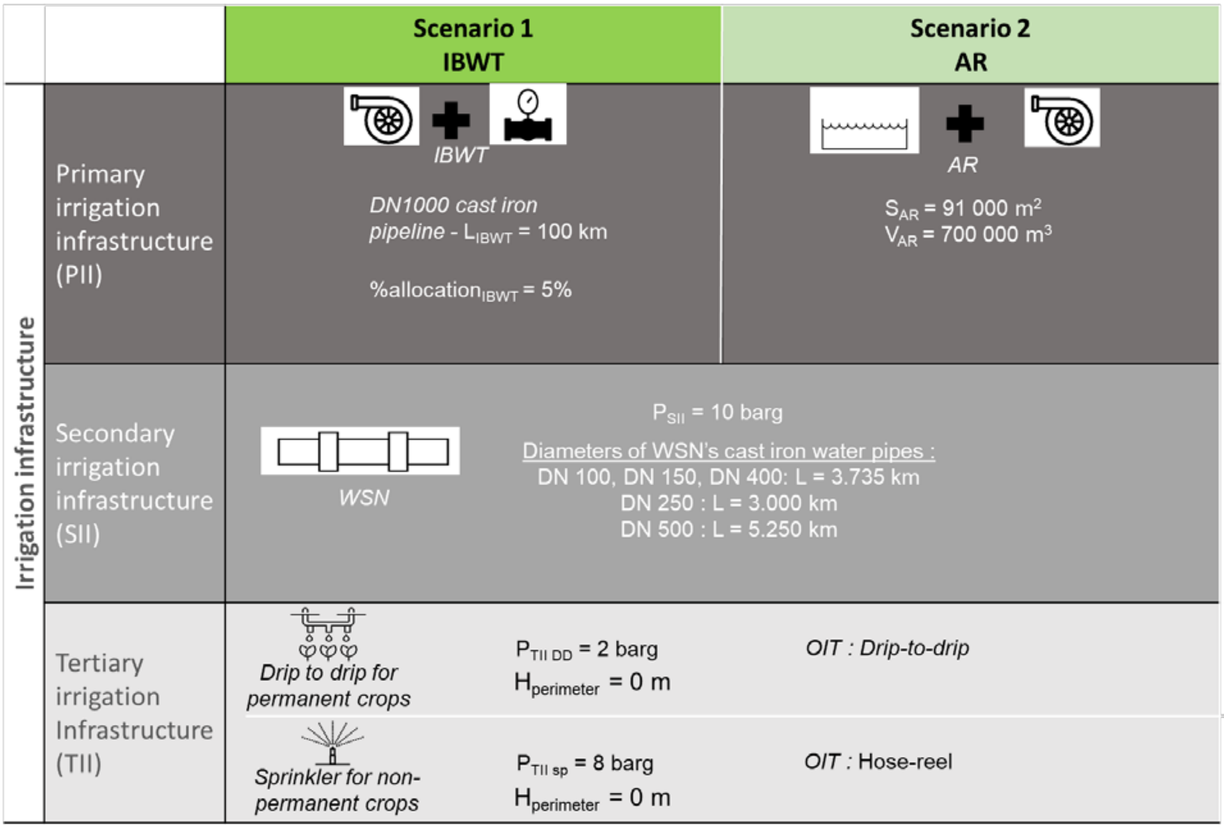


Figure 2 Main design parameters for the hydraulic infrastructures
L_{IBWT} (km), the length of IBWT's buried water pipeline; $\%allocation_{IBWT}$, the share of IBWT impacts which is allocated to the Scenario 1; S_{AR} (m^2), AR's surface; V_{AR} (m^3), AR's volume; $P_{TII\ sp}$ (barg), the pressure of the sprinkler OIT; $P_{TII\ dd}$ (barg), the pressure of the drip-to-drip OIT; P_{SII} (barg), the pressure inside the WSN; and $H_{perimeter}$ (m), the altitude of the agricultural perimeter with respect to IBWT pumping station.

The hydraulic infrastructure LCIs were subdivided into two separate stages, i.e. i) the construction and ii) the operation phase. Inventories are based on the Ecoinvent V3 cut-off database.

2.2.2.1. Water infrastructure construction

Lifetime is an important parameter in the environmental assessment of an infrastructure (Risch et al., 2021). In this study, AR, IBWT and the WSN lifetimes are presumed to last 50 years. All the data concerning the lifetimes of the different parts of the hydraulic infrastructures are provided in Table S. 4 of the S.I..

According to expert knowledge, all the civil engineering operations were supposed to take place on soft grounds for IBWT and WSN. For AR, these operations were considered to take place on 5% (v/v) rocky grounds. Table S. 2 of the S.I. indicate the different civil engineering operations as well as the type of material needed for the construction of the hydraulic infrastructures. An aggregated dataset for the LCI of hydraulic infrastructure construction i.e. the amount of material and repair rates as well as the names of the LCI processes of materials and of their manufacturing processes in the Ecoinvent database, is available in Table S. 4 of the S.I.. For each of the civil engineering operations, working crews were formed including all the machines and their respective energy consumption for one hour of work (Table S. 3 of the S.I.).

All the material was considered to be provided by the globalized market except for the cast-iron pipes that are manufactured in France, and for which specific transportation distances were chosen. Adequate manufacturing processes as well as scenarios dedicated to the end-of-life of materials (disposal in a landfill, recycling or incineration) were selected for these materials, as described in (Risch et al., 2015).

2.2.2.2. Water balance and energy consumption

The operation phases of water infrastructure are characterized by water and energy consumption. Figure 3 shows the annual flows that need to be taken into account to achieve a water balance in TII and PII. No water loss is assumed to occur in the SII as well as in the IBWT water pipeline. Only the PII consumes energy, which is sourced from the French medium voltage electricity mix. This consumption depends on the hydraulic design defined in Figure 2.

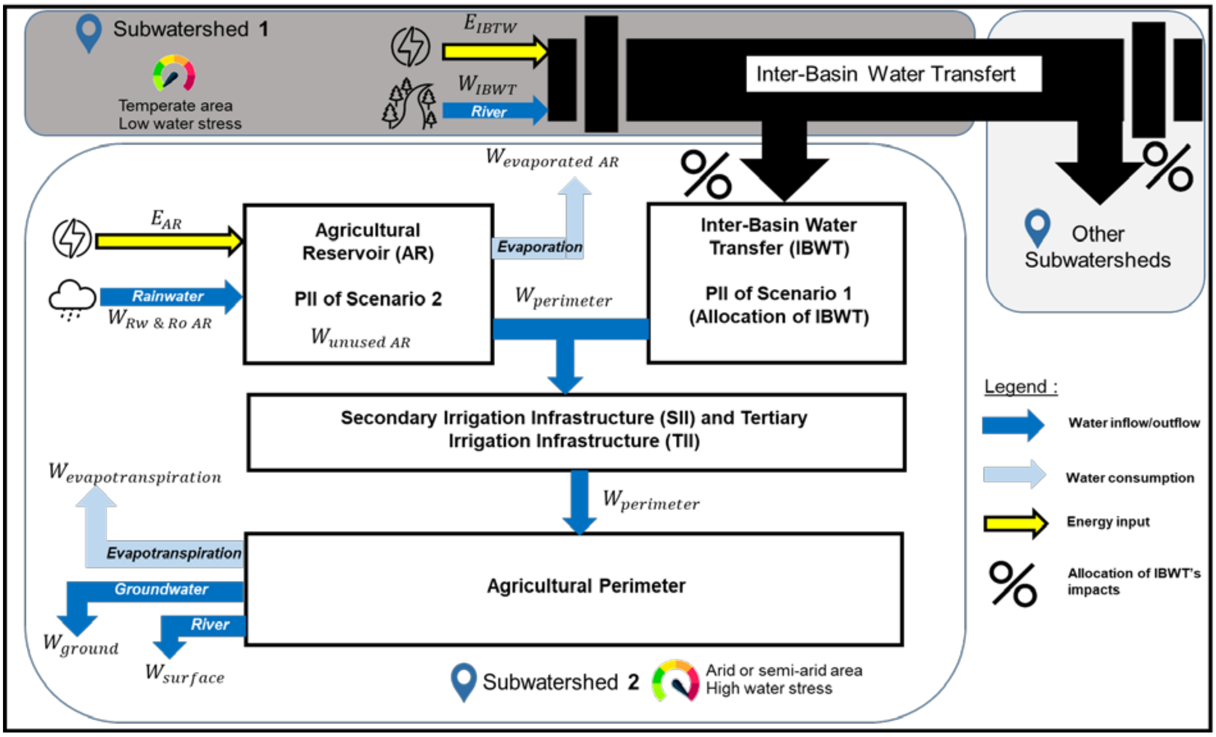


Figure 3 Water balance and energy calculation framework

$W_{evapotranspiration}$ (m³/yr), the flow of water that is evapotranspirated over the agricultural perimeter; $W_{surface}$ and W_{ground} (m³/yr), the water losses of the agricultural perimeter due to the efficiency of irrigation; and $W_{perimeter}$ (m³/yr), the total quantity of water that needs to be supplied to the agricultural perimeter for irrigation ; $W_{Ro\ \&\ Rw}$ (m³/yr), the quantity of rainwater and run-off water filling the AR; $W_{evaporated\ AR}$ (m³/yr), the share of water that is evaporated from the AR open-surface; $W_{unused\ AR}$ (m³/yr), the water of the AR that is not consumed and stored for the next year; W_{IBWT} (m³/yr), the total quantity of water that is circulating in the IBWT infrastructure; E_{AR} (Wh/yr), the annual energy used at AR pumping station; and E_{IBWT} (Wh/yr), the annual energy consumption at the IBWT pumping station.

At TII, water is either consumed directly by the crops through evapotranspiration or lost through run-off to the surface and groundwater compartments. Evapotranspiration data are already included in the Agribalyse 3 (Koch and Salou, 2020) and WFLDB databases (Nemecek et al., 2019). An irrigation efficiency factor is applied to account for water losses. According to (Nemecek et al., 2019), this factor varies between 0.75 for sprinkler irrigation and 0.9 for the drip-to-drip irrigation. The water losses include run off to rivers (80%) and to groundwater compartments (20%).

The water balance and energy consumption related calculations are in the S.I..

2.3. Performance indicators and LCIA impacts methods

As previously mentioned, one of the main adaptations of the LCA methodological framework for assessing territorial systems is to quantify eco-efficiency ratios. The following section describes their necessary indicators, i.e. the three main functions of the studied territory and their resulting environmental impacts.

For biomass production, data on crop yields are used. These are directly obtained from the information given in Table S. 1 of the S.I.. For the economic function, the agricultural turnover was assessed using market price data for the studied crops, sourced from the French agricultural statistics, which are provided in Table 3. Finally, the land planning function is estimated through the total agricultural perimeter area, i.e. 700 ha in all scenarios.

Table 3 Market price of crops

Type of crop	Market price (€/kg)	Year	Source
Corn	0,17	2019	(Agreste, 2019)
Wheat	0,16	2019	(Agreste, 2019)
“Pays d’Oc” PGI grapevine	0,70	2019	(DRAAF Occitanie, 2020)
“Languedoc” CDO grapevine	1,22	2019	(DRAAF Occitanie, 2020)

Concerning environmental impacts, both midpoint and endpoint indicators are quantified with the IMPACT World+ method (Bulle et al., 2019) to address the different sub-objectives described in Table 1. IMPACT World+ was chosen over the ReCiPe 2016 LCIA methods (Huijbregts et al., 2017) because it includes the latest development in terms of impact assessment (Bulle et al., 2019), such as the AWARE model (Boulay et al., 2018) and the USEtox model (Rosenbaum et al., 2008), which are the present consensual way of assessing water scarcity as well as ecotoxicity and human toxicity impacts (European Commission - Joint Research Centre, 2012). Endpoint indicators facilitate the comparison of alternatives because they reflect the differences between causes of stress further down the cause-effect chains that directly affect a society (i.e. human health, ecosystem quality and resources). Then, midpoint indicators allow for the identification of issues related to the water-energy-infrastructure nexus. The IMPACT World+ v.1.46 actually available for download on SimaPro software does not include an endpoint indicator for the resource area of protection. Hence, the “Fossil and Nuclear Energy Use” and “Mineral Resource Use” midpoint indicators were employed as proxies. The AWARE characterization factors (CF) for the French Mediterranean area are sourced from a GIS (Geographic Information System) map (WULCA, 2021), i.e. 46.6 for the arid sub-watershed and 1 for the temperate watershed. Penoxsulam (CAS No. 219714-96-2) a herbicide used in the CDO and PGI grapevines was not characterized in the IMPACT World+ method, thus not quantified in this study. It should not significantly affect the impact assessment because it only represents less than 0.02% in weight of the total amount of phytosanitary products used in both CDO and PGI grapevine cultivation.

3. Results

In this section, the results of the study are presented according to the three main objectives defined in *Table 1*.

3.1. Sub-objective 1: Eco-efficiency comparison

The eco-efficiency ratios are calculated according to the different services provided by the land planning scenarios in Table 4. The higher the eco-efficiency of one scenario, the better it is from an environmental point of view.

Figure 4 compares the eco-efficiencies of the three scenarios in relative terms (i.e. normalized by the best scenario).

Table 4 Services provided by the three land planning scenarios

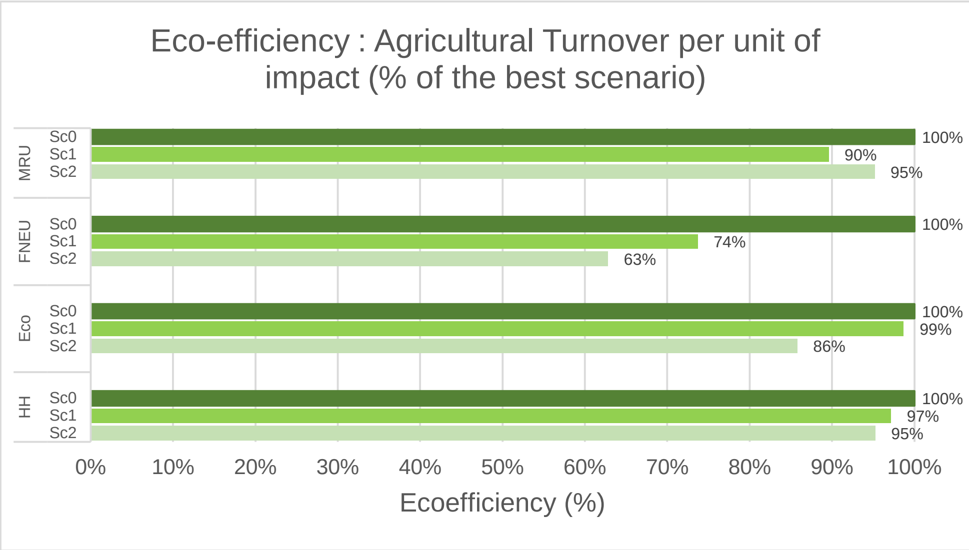
Territorial functions	S0 (no irrigation)	S1 (IBWT)[(1)]	S2 (AR)[(2)]
Area harvested (ha)	700	700	700
Mass of agricultural products (kTons)	3,34	4,56	4,56
Agricultural turnover (M€)	2,14	2,40	2,40

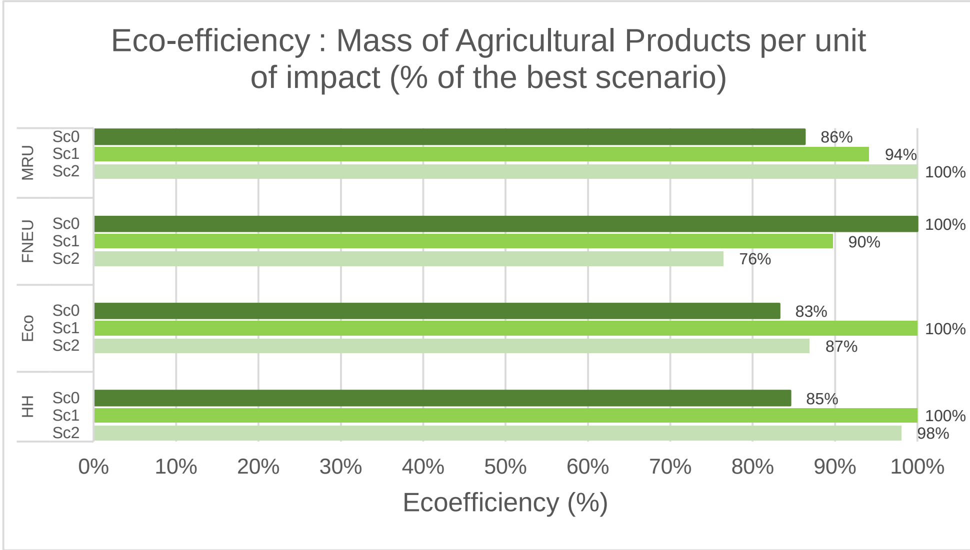
(1) IBWT : "Inter-Basin Water Transfer"

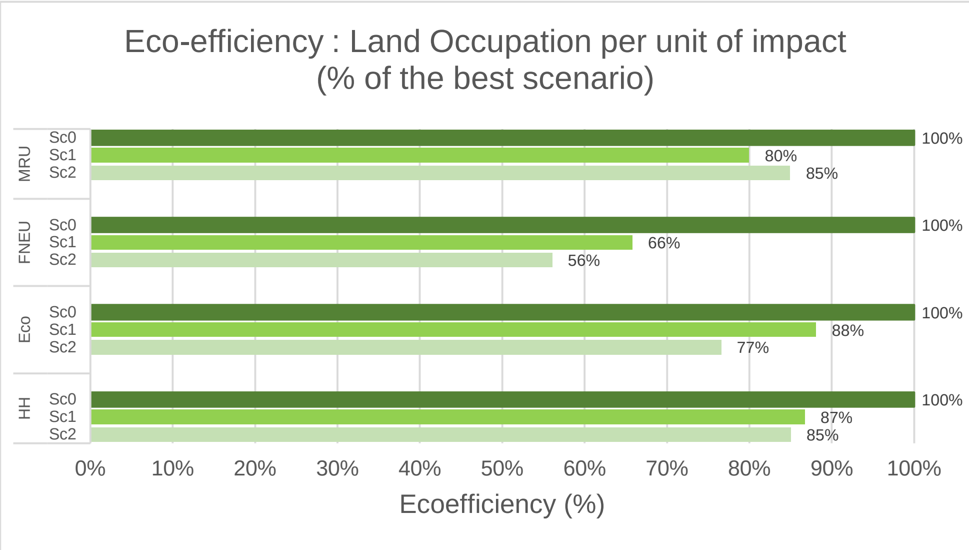
(2) AR : "Agricultural Reservoir"

The results for the environmental performance of a scenario depend on the investigated territorial function. For the Land Occupation (LO) function, Scenario 0 is better than the irrigated scenarios for all environmental impacts considered. After Scenario 0, Scenario 1 presents best performance, except for impacts on mineral resources. This is due to the different impacts induced by the hydraulic infrastructures. The same conclusion arises for the economic function, where the Scenario 0 turnover is similar to scenarios 1 and 2, mitigating the differences in biomass production between scenarios. Indeed, a greater part of the agricultural perimeter is occupied by CDO grapevine, which is rather focused on quality than on quantity in the non-irrigated scenarios than in the irrigated ones. Moreover, the market price of CDO grapes is about 7 fold higher than for corn and wheat and around 1.75 times higher than for PGI grapevines.

On the contrary, for biomass production, the calculated eco-efficiency is higher for both irrigated scenarios than for the non-irrigated when considering the Ecosystems (Eco), Human Health (HH) and Mineral Resource Use (MRU) indicators. The reason is that the higher quantity of MAP of the irrigated scenarios counteracts their higher environmental impacts in comparison with the non-irrigated scenario. They therefore have higher eco-efficiencies. Considering the environmental impacts for the Fossil and Nuclear Energy Use (FNEU) indicator, the fact that Scenario 0 does not use energy for pumping water counteracts its low amount of provided service, therefore its eco-efficiency is higher than for the irrigated scenarios.







Legend:

Scenario 0: no irrigation

Scenario 1: irrigation with an Inter-Bassin Water Transfer (IBWT)

Scenario 2: irrigation with an Agricultural Reservoir (AR)

Figure 4 Eco-efficiencies of the studied scenarios

HH: "Human Health"; Eco: "Ecosystems"; FNEU: "Fossil and Nuclear Energy Use"; MRU: "Mineral Resource Use"

Figure 5 illustrates the contribution of the hydraulic infrastructures to the total impact of Scenarios 1 and 2, for the LO function. The share of the total scenario impacts relative to the hydraulic infrastructure is quite low for all environmental indicators except for the FNEU, because of energy use at the PII pumping stations.

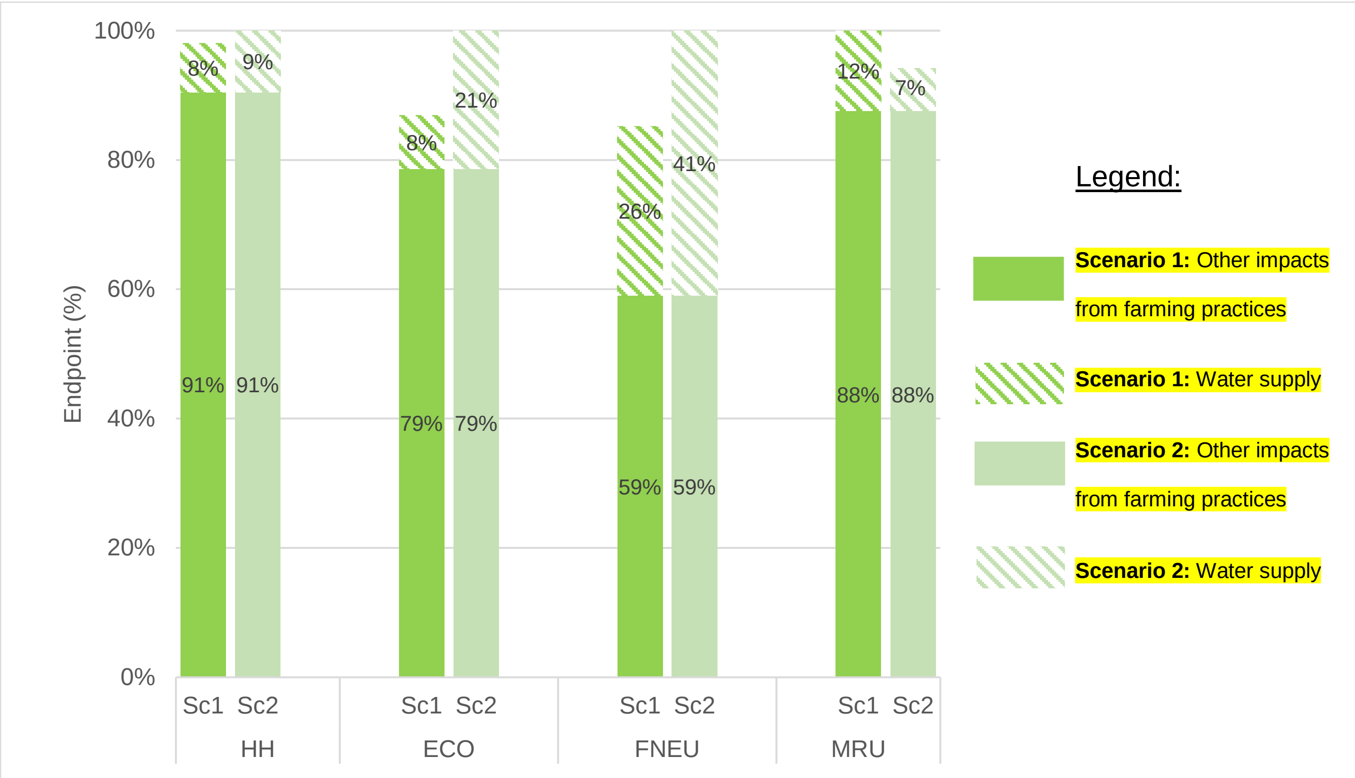


Figure 5 Contribution analysis of scenarios 1 and 2

3.2. Sub-objective 2: assessing the water-energy-infrastructure nexus

A contribution analysis is carried out to identify the main impacting stages in infrastructure projects. Figure 6 compares the environmental impacts of Scenarios 1 and 2 for the Land Occupation functional unit at midpoint level. The difference between their impacts resides in their respective water-energy-infrastructure nexus.

For the water part of the nexus, unlike the AR, the IBWT supplies water from a low water stress area with a low AWARE CF. Thus, for Water Scarcity (WS), this leads to an avoided impact for the Scenario 1 “Irrigation water”.

For the energy part of the nexus, the impacts on the AR (ie. “Energy – PII”) are about 2 fold higher than on the IBWT for each midpoint indicator, because the allocated energy use of the IBWT is approximately half that of the AR.

Both scenarios have the same SII and TII, hence the environmental performances of their infrastructure reside in their respective PII, whose impact assessment results are more mixed. Indeed, for Climate Change, short term (CC, st), Climate Change, long term (CC, lt), Fossil and Nuclear Energy Use (FNEU), Ozone Layer Depletion (OLD), Water Scarcity (WS), Freshwater Acidification (FA), Terrestrial Acidification (TA) and Ionizing Radiation (IR) both scenario PIIs have almost the same impacts. For some of the midpoint indicators (Mineral Resource Use (MRU), Photochemical Oxidant Formation (POF), Human Toxicity cancer (HTc), Human Toxicity non cancer (HTnc), Marine Eutrophication (ME) and Particulate Matter Formation (PMF)), the IBWT performs worse than the AR because of the high amount of cast-iron necessary in its infrastructure. On Freshwater Ecotoxicity (FEco) and Freshwater Eutrophication (FE), AR performs worse than IBWT because the amount of bronze and copper necessary for equipping the AR pumping station is fully allocated to the studied territory. The same applies to Land Transformation, biodiversity (LT, bio) and Land Occupation, biodiversity (LO, bio) because of the high amount of land occupied by AR, unlike the IBWT, which involves a buried pipeline.

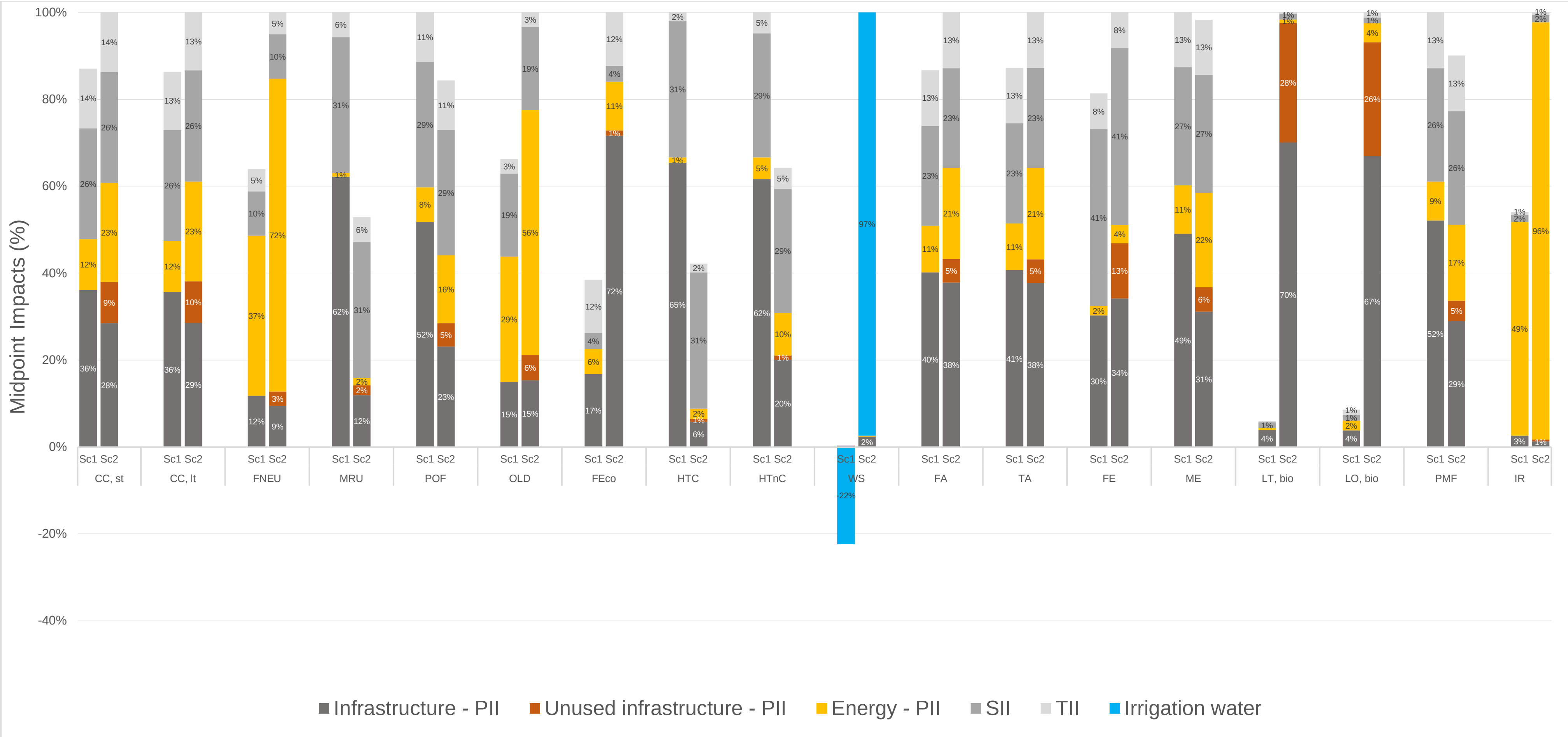


Figure 6 Environmental impacts at midpoint for Scenario 1 and 2 water supplies

CC, st: "Climate Change, short term"; CC, lt: "Climate Change, long term"; POF: "Photochemical Oxidant Formation"; OLD: "Ozone Layer Depletion"; FEco: "Freshwater Ecotoxicity"; HTc: "Human Toxicity cancer"; HTnc: "Human Toxicity non cancer"; WS: "Water scarcity"; FA: " Freshwater Acidification"; TA: "Terrestrial Acidification"; FE: "Freshwater Eutrophication"; ME: "Marine Eutrophication"; LT, bio: "Land Transformation, biodiversity"; LO, bio: "Land Occupation, biodiversity"; PMF: "Particular Matter Formation"; IR: "Ionizing Radiation"; PII: "Primary Irrigation Infrastructure"; SII: "Secondary Irrigation Infrastructure"; TII: "Tertiary Irrigation Infrastructure"

3.3. Sub-objective 3: Design parameters to define conditions under which a given hydraulic project performs better

Section 3.2 results suggest that PII dominates the impacts of both hydraulic projects due to the high consumption of material and energy. However, these impacts are highly dependent on design parameters that can differ from one territory to another, especially for the IBWT, such as W_{IBWT}, and L_{IBWT}. The Equation 1, achieved through the use of equations S.11-S.15 of the S.I., was used to determine the sets of W_{IBWT} (or the corresponding $\%allocation_{IBWT}$) and L_{IBWT} for which the IBWT alternative is better than the AR.

$$L_{IBWT} = \frac{\left(\frac{1}{\%allocation_{IBWT}} * \left(A - B - E * \left(F + H_{perimeter}\right)\right) - C\right)}{D + \frac{G}{\%allocation_{IBWT}}} \qquad (1)$$

Where A, B, C, D, E, F and G are groups of parameters described in equations S.16-S.23 in the S.I.. A contains the impact of the AR infrastructure; B contains the impact of water that is withdrawn by the IBWT pumping station ; C contains the impact of the IBWT pumping station's infrastructure ; D contains the impact of the civil engineering as well as the materials necessary for the IBWT water pipeline ; and E , F, G contain the impact of the French medium voltage electricity mix used to power the IBWT pumping station.

Figure 7 illustrates the environmental break-even area between both infrastructures, when $H_{perimeter} = 0\ m$. Each of the break-even areas is bordered by tipping curves comprising tipping points. These points correspond to the length of IBWT water pipeline, for a given $\%allocation_{IBTW}$, where the endpoint indicators of the water supplied by the IBWT and by the AR are equal.

The Ecosystems break-even area can only be achieved with unrealistic values of ($\%allocation_{IBWT}, L_{IBWT}$), so it was not included in the following analysis. Hence, IBWT always performs better than AR on Ecosystems damages. As mentioned in section 3.2, IBWT always performs better than AR on WS, therefore it was also not included in the following analysis. The four break-even areas presented in Figure 7 can be subdivided in two types of information that can help support decision making, i.e. i) *Certain areas*, where a hydraulic infrastructure is better than the others for all 4 indicators, ii) *Uncertain areas*, where a decision cannot be made about the best environmental performance of a hydraulic infrastructure, because one water supply is not better than the others for all 4 indicators. *Certain areas* are within break-even area 5 where the IBWT water supply is better than AR. Therefore, considering realistic design parameters, IBWT can present better environmental performances than AR. *Uncertain areas* are within break-even areas 1, 2, 3 and 4. The set of parameters, for which the results in section 3.1 and 3.2 were computed, is located in area 4 (symbol +). This justifies why IBWT is only better than AR for indicators HH, FNEU and Eco and not for MRU.

Results in section S.1.2 of the S.I. indicates that $H_{perimeter}$ only affects the energy required at the IBWT pumping station when the altitude of the irrigated perimeter increases.

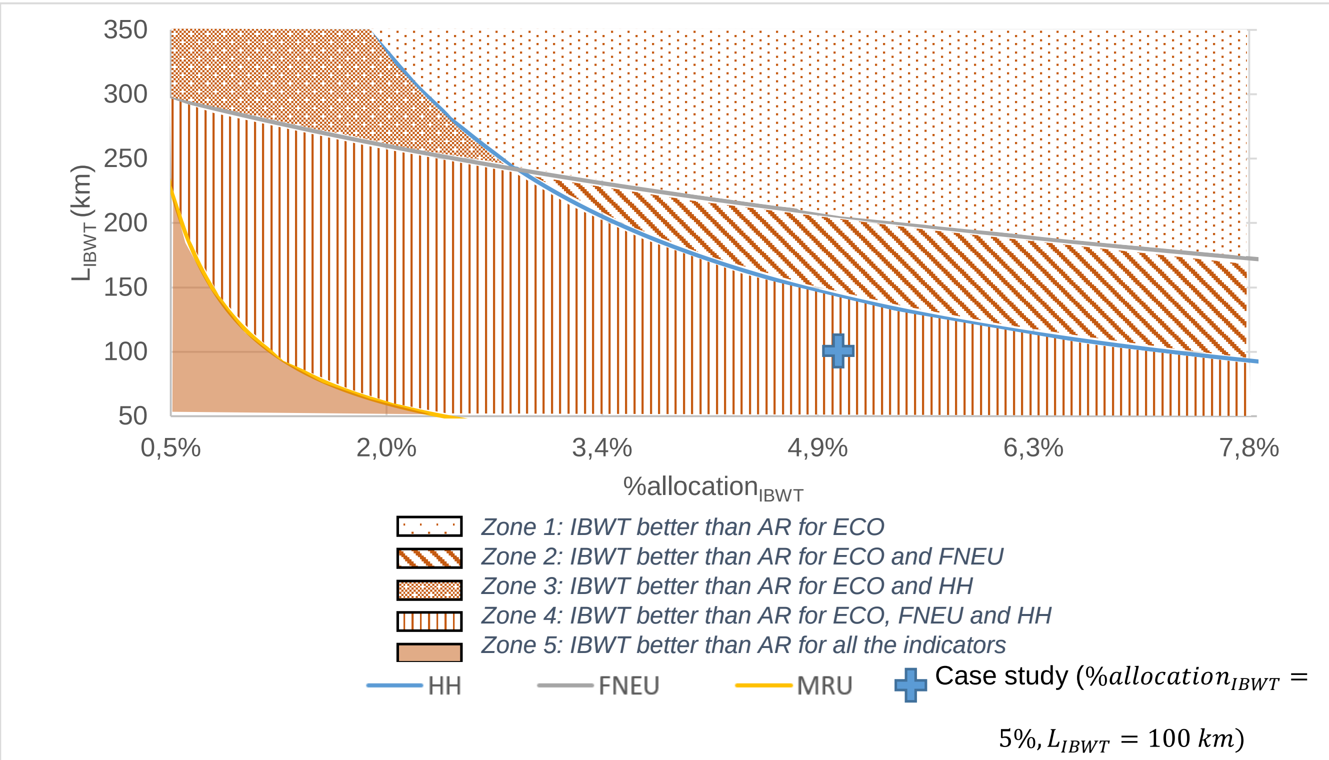


Figure 7 Environmental break-even area for which IBWT water supply is better than AR for H_{field} = 0 m
The delineation of this graph is explained in the section 1.2 of the S.I.

4. Discussion

4.1. Supporting decision making

This paper proposes a novel approach for defining the conditions under which the environmental performances of a hydraulic project varies higher or lower than another type of project, while taking into account biophysical constraints. The tipping lines that were computed according to the main parameters of the designed inter-basin transfer illustrate that the impacts of this type of project can vary both higher or lower than the impacts of a project based on a local water resource such as an agricultural reservoir. Such studies are necessary for planners to identify the best options within a given context, while other parameters related to agricultural practices or land use patterns could be taken into account in future studies.

One main objective of the T-LCA framework is to compare the environmental performance of land planning scenarios. For this purpose, eco-efficiency is a metric for quantifying both the services provided by different scenarios and the resulting environmental impacts (Loiseau et al., 2018). In this study, there is no scenario in which the eco-efficiency remains maximal for the three considered territorial functions. These functions have been defined according to the scientific literature, and other functions could be identified from real case studies in consultation with stakeholders.

This study also highlighted that T-LCA can be used by territorial planners to identify trade-offs in the water-energy-infrastructure nexus. Section 3.2 inferred that an environmental analysis should not focus on only one aspect of the water-energy-infrastructure nexus before a decision is taken concerning the construction of a specific type of hydraulic infrastructure. Indeed, unlike the energy and water components of the nexus, the analysis cannot be as straightforward for the infrastructure component because IBWT does not perform better than AR at all the midpoint indicators.

4.2. Considering spatio-temporal variability

4.2.1. In LCI

LCIs are adapted to the French context, particularly for agricultural production and the electricity mix. The relatively low impacts of the water supply in comparison with farming practices are partly due to the use of the French electricity mix, which comprises 70% nuclear-based electricity (ADEME, 2018), a low-carbon form of energy. Therefore, by choosing a more carbon-intensive electricity mix, as found in China for example, the impacts of the water supply could increase, thus modifying the results of this study (Leão et al., 2019a). For agricultural production, more detailed modelling would allow for local specificities to be better accounted for, such as the pedo-climatic conditions of the studied territory, or the agricultural practices implemented by the stakeholders. To enhance spatial representativeness, regionalized LCI could be developed based on interviews of local stakeholders as in Borghino et al. (2021) or spatial databases (Nitschelm et al., 2016).

In addition, the inter-annual variation of crop yields has not been considered in this study. Indeed, yield data for grapevines were sourced from 2013 data (Agreste, 2016). Wheat and corn yields were also based on data over an average of 4 years: 2005-2009 for corn (Koch and Salou, 2020) and 2014-2019 for wheat (Nemecek et al., 2019). The required amount of water fluctuates between April and August depending on the irrigation periods of the different crops, with increasing needs from June to August. Yet, the water requirement of the cultivated area was overestimated, hence so was E_{AR}. Moreover, more water circulates through the IBWT during the irrigation period than during the rest of the year, when agricultural needs are lower. The annual quantity of water circulating through the IBWT was therefore also overestimated.

4.2.2. In LCIA

Spatial variability was only considered for quantifying the midpoint impact on water resources with the AWARE model, at the sub-watershed scale. This significantly improves the calculation of the impact, since there are strong regional discrepancies in terms of water resource availability.

However, temporal variability was not taken into account in this study as annual characterization factors (CF) were chosen for each of the sub-watersheds. Selecting monthly CFs has a significant impact on the Water Scarcity (WS) indicator, as indicated in Table S. 9 of the S.I., where WS calculated with annual or monthly CF are compared. Indeed, for Scenario 2, the consideration of a winter CF for the water filling of the AR can lead to an avoided impact. Yet, these results are preliminary and a better assessment of the local hydrology would be necessary. Indeed, the global impacts of small reservoirs on hydrology are estimated to represent 5% of the mean discharge and 44% of the low flow (Habets et al., 2018), and should be fully addressed in AWARE calculations. Spatialized CFs for site-dependent impacts such as eutrophication or acidification could also have been employed for better territorial representativeness (Nitschelm et al., 2016). This could be done by applying new regionalized LCIA methods such as IMPACT World + (Bulle et al., 2019) or LC-IMPACT (Verones et al., 2020), when their full development will be achieved.

4.3. Water resource in LCIA methods

The impact induced by water resource consumption is crucial for the comparison between performances of the studied scenarios. In the IMPACT World+ method, the terrestrial ecosystems are only affected by water use if it is extracted from the ground because it affects the moisture of soils, which in turn impacts the growth of given plant species (Zelm et al., 2011). Therefore, the impacts on terrestrial ecosystems remain negligible in this study because the irrigation water originates from surface water. In ReCiPe 2016, impacts of water consumption on terrestrial ecosystems are based on the Net Primary Production (NPP) of vascular plants limited by water, and encompass all water bodies (Pfister et al., 2009). For aquatic ecosystems, both endpoint LCIA methods are based on the works of (Hanafiah et al., 2011) where the effects of changes in river discharge on freshwater fish species are considered. Since lotic habitats are most vulnerable to consumptive water use (Vörösmarty et al., 2010), it would also be worthwhile, in the long run, to use the HCP (Habitat Change Potential) midpoint impact category in the study. This comprises the effects of water consumption on instream species (Damiani et al., 2021). In LC-IMPACT, only the impacts of both surface water and groundwater consumption on wetlands are considered (Verones et al., 2020). Recent investigations propose to consider the impacts on terrestrial ecosystems that entail the conversion of a terrestrial habitat into an aquatic habitat (Dorber et al., 2020). Applied to AR, these new spatialized CFs would increase the impacts of AR on terrestrial ecosystems while having a beneficial effect on aquatic ecosystems. .

4.4. Taking into account the effects of global changes

Within the next decades, global changes such as climate change are expected to intensify the variations in meteorological parameters (Mbow et al., 2019), which, in turn, could lead to a rise in inter-annual variations of the scenario eco-efficiencies. Therefore, prospective T-LCA of land planning scenarios with long-lasting infrastructures would result in the use of more robust data and in the consideration of potential environmental feedbacks. The effects of the different types of stress induced by the evolution of meteorological conditions on crop development should be taken into account. Prospective crop yields could be sourced from real-life experiments, for example from a phytotron (Niero et al., 2015) or from crop growth models such as Aquacrop (El Chami and Daccache, 2015) and CropSyst (Tendall and Gaillard, 2015). Due to the spatio-temporal dynamics of water resources, inter-annual variations of water availability should also be taken into account. A projection of future availability could be sourced from databases as has been done by (Leão et al., 2019b) with the Prospective Water-Supply Mix (P-WSmix). A modification in the future water availability would lead to a difference between the values of present and future AWARE CF.

5. Conclusion

This study aimed to assess, from an environmental point of view, the conditions under which hydraulic projects can be considered as an efficient option in order to secure the water supply of agricultural areas. However, as the different scenarios do not provide the same range of services, it is impossible to perform conventional LCA for comparison purposes on the basis of the same functional unit. The present paper demonstrates the feasibility and relevance of the territorial LCA approach as well as the associated eco-efficiency concept for comparing such scenarios. This was achieved by comparing three different theoretical land-planning scenarios, i.e. without irrigation (scenario 0), irrigated by an IBWT (scenario 1) or by an AR (scenario 2). The major highlights and main recommendations and challenges to conduct territorial LCA approaches are listed in the following:

- T-LCA provides eco-efficiency metrics that provide exhaustive information about the environmental performance of land-planning scenarios for three territorial functions in this paper, “agricultural turnover”, “mass of agricultural products” and “land occupation”. Depending on the selected function, the environmental performance of the three scenarios vary. For functions “agricultural turnover” and “land occupation”, scenario 0 has a better eco-efficiency over all the endpoints indicators. For function “mass of agricultural products”, the results are more contrasted : scenario 0 is better on Fossil and Nuclear Energy Use, scenario 1 is better for Human Health and Ecosystems, and scenario 2 is better on Mineral Resource Use. These outputs allow the identification of trade-offs between different functions and environmental impacts, and can support local planners and stakeholders to select scenarios that maximize the main function of their project while limiting the effects on other functions.
- The T-LCA framework identifies trade-offs in the water-energy-infrastructure nexus. Overall, the water for irrigation supplied from IBWT performs better than from AR regarding most of the end-point indicators (Ecosystem, Human Health and Fossil & Nuclear Energy Use), because only a part of its total impact is allocated to the studied territory. Results are less advantageous for the Mineral Resource Use, due to the high amount of cast-iron necessary in IBWT infrastructure.
- Moreover, T-LCA could also apply to the eco-design of large-scale hydraulic infrastructures. Indeed this framework can provide flexible environmental impact assessments (i.e. tipping lines) that take into account several design parameters, thus contributing to the choice of an infrastructure design.

- The main limitation of this study is that the LCIs are built according to static environmental conditions. Therefore the LCIs do not account for the effects of environmental dynamics (i.e. climate, hydrology and soil) nor do they include the possibility of changes in the ecosphere (e.g. climate change or water resource depletion), which are expected to further intensify during the long lifetime of the hydraulic infrastructures. For this reason, it is necessary to involve direct and indirect environmental feedback into the T-LCA framework for the choice, without risk of regret, of a specific type of long-lasting hydraulic infrastructure.

6. Associated contents:

The S.I. contains the LCI data set for PGI and CDO grapevines as well as all the crops yields, information about the different civil engineering operations necessary for the construction of the hydraulic infrastructure as well as a condensed LCI dataset for them. The S.I. also contains the water balance and energy consumption related calculations as well as the equations and curves supporting section 3.3.

7. Acknowledgments:

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