Integrated Qualitative and Quantitative Analysis of Causal Urban Food-Water-Energy Relations towards more Climate-Resilient Cities

Romana Stollnberger, Ernst Gebetsroither-Geringer, Ulrike Magerl

(DI Romana Stollnberger, AIT Austrian Institute of Technology, Digital Resilient Cities; Wien, AT, romana.stollnberger@ait.ac.at)
(Dr. Ernst Gebetsroither-Geringer, AIT Austrian Institute of Technology, Digital Resilient Cities; Wien, AT, ernst.gebetsroither@ait.ac.at)
(Ulrike Magerl, BSc, AIT Austrian Institute of Technology, Digital Resilient Cities; Wien, AT, ulrike.magerl@ait.ac.at)

1 ABSTRACT

Currently, the world is facing great challenges in terms of securing water, energy and food for all. With continuous increase in urbanisation and and changed lifestyles, the demand within the three sectors food, water and energy (FWE) in cities is increasing as well (Sukhwani et al., 2019). Due to the limited availability of natural resources, the pressure on urban land use is equally increased, thus more attention needs to be given to sustainability and resource efficiency. Furthermore, climate change and the related increased frequency of extreme weather events such as stormwater events and/or dry periods pose additional challenges for infrastructure and (agricultural) land use as well as for the quality of life. These challenges call for more systemic, integrated and cross-sectoral approaches helping to build resilient urban systems. These approaches should focus more on a holistic urban system transformation, rather than tackling problems within one sector. Thus, the main goal of reaching a sustainable future should be to create integrated, informed and well-coordinated interventions to support cities to become more climate resilient.

As a response to the problem setting, the concept of FWE Nexus emerged. The Nexus describes and analyses the interlinkages between the three sectors, with the goal to identify potential synergies and minimise trade-offs between the three sectors (Hoff, 2011).

The paper discusses a number of methods on how to describe the FWE system: Firstly, to show how different elements in the entire FWE system are interrelated and to create a common system view among the involved stakeholders, a qualitative system analysis, has been carried out. This qualitative system analysis enables experts (from FWE sectors, city authorities, urban planners) to understand the causal relations and the feedbacks between the system elements. Thus, to cope with the challenges and system immanent drivers, a basis for the discussion and development of strategies is established. The qualitative analysis was also used to gain a specific view on the differences between different case study regions. Secondly, based on this qualitative analysis, a more specific quantitative GIS-based analysis of land use changes and resulting water demand has been performed as input for a simulation model. This model will be used to analyse the impacts of spatial planning scenarios for the sustainable resources management and shall support urban planners to create more resilient cities and regions.

Keywords: FWE Nexus, population growth, land use change, urban agriculture, qualitative and quantitative system analyses and simulation

2 BACKGROUND AND OBJECTIVE

Rapid urbanisation, growing population and the evolving challenges posed by climate change are causing an increased need for security of supply of water, energy and food for all. Due to the limited availability of natural resources, the pressure on urban land is increasing and competition for land use is created. This requires a stronger focus on the sustainable and efficient use of the resource land. Bren d´Amour et al.(2017) concluded that the rapid expansion of cities will result in the loss of some 300,000 square kilometres of particularly fertile farmland worldwide by 2030. This arable land, which will probably disappear in the future, is almost the size of Germany. Furthermore, climate change and the related increased frequency of extreme weather events such as stormwater events and/or dry periods, pose additional challenges for infrastructure and (agricultural) land use as well as for the quality of life.

In this context, the Sustainable Urbanisation Global Initiative (SUGI)/FWE-Nexus call was jointly established by the Belmont Forum and the Joint Programming Initiative Urban Europe. Within this call, the AIT Austrian Institute of Technology GmbH is involved in the project IN-SOURCE (INtegrated analysis and modeling for the management of sustainable urban FWE ReSOURCEs), which aims at developing a joint urban data and modelling framework that will help cities and regions to analyse and characterise the FWE-Nexus interdependences. This framework is based on the extension of semantic 3D city models as well as on

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geoinformation applications to be developed and applied in the three case study regions: Vienna, New York and the administrative district Ludwigsburg as a metropolitan region. The paper focuses on the case study region Vienna.

The objective of the qualitative system analyses, the causal relation analyses, are (i) understanding the system elements interaction and feedbacks in the entire FWE-System, (ii) building a joint vision of these system elements interactions between the project partners, (iii) supporting the discussion with stakeholders in interactive workshops.

3 QUALITATIVE SYSTEM ANALYSIS

Causal relations can be expressed by using the method of Causal Loop Diagrams (CLDs). The approach became famous during the 70ies as they have been used by the Club of Rome to explain the system structure of the developed World3 models (Meadows et al., 1972).

CLDs use a simple "language" to describe dynamic systems and can be used to analyse, communicate and discuss possible system behaviour. Interrelations between system elements expressed as arrows with polarities (+, -) and time delays are the components used to visualise the entire system. CLDs have no starting point or end point, they are rather closed circuits. The system elements are entities, which can increase or decrease. The arrow with the polarity indicates how an entity changes when the influencing entity changes. A link marked positive (+) indicates a positive relationship and a link marked negative (-) indicates a negative relation. A positive causal link means the two entities change in the same direction, i.e. if the entity in which the link starts decreases, the influenced entity also decreases. Similarly, if the entitiy in which the link starts increases, the influenced entity increases as well. A negative causal link means the two entities change in the opposite direction: if the entitiy in which the link starts increases, the influenced entity decreases, and vice versa. With these simple "rules" complex system structures can be visualised. For the CLDs developed in IN-SOURCE and shown in this paper we used coloured arrows (blue) and solid lines for "+" interrelations and red arrows and dashed lines for "-" to increase the readability in the paper.

The aim of the FWE CLDs which are specifically developed for each case study region is to get a more appropriate view about the most important interactions. The diagram neither consists of all possible system elements nor all connections as this would make it hardly manageable to interpret. For example, we didn´t differentiate between different water qualities which would have restricted use for different purpose only (drinking water, treated waste water, rain water etc.).

The decision of which element/parameter/factor is important, was met according to different information: expected system element changes, e.g. population changes (increases or decreases), effects of climate change, together with challenges the case study areas are currently facing, e.g., mitigation of heat islands, air pollution. Other important factors to identify important links were the interest of the relevant stakeholders and available tools to quantify the causal relations. Within the specific CLDs for each case study region we indicated the more important links by increasing the thickness of the arrows as the specific CLD for Vienna in Figure 1 shows.

3.1 Causal FWE relations in Vienna

The causal relations diagram for Vienna was established under the assumption of a growing urban population. According to forecasts, Vienna will grow moderately by 289.000 people (about 16%) over the next three decades and the population of the city will be about 2,200,000 in 2048 (MA23, 2018). Additionally, climate change has been taken into consideration as a determining factor that will change the future system logic. The CLD shows relations between the three systems of water, energy, and food and challenges Vienna is currently facing (e.g. heat islands, air pollution, urban land availability). Due to the high complexity of the topic, this analysis can only show a few relevant connections that are primarily connected to the Nexus. Figure 1 shows the causal FWE relations that have been assigned to the three systems using different colors.

3.1.1 Urban Food System

Population growth would also increase the related Food consumption which in return reduces the Food availability. To meet the increasing demand for food, importing food results in an increasing transportation demand which causes additional CO_2 emissions what can be called a Nexus effect with the energy system.

Another option to supply the city with sufficient food is to increase Urban Agriculture (UA) which again increases the traffic to transport the food and affects the energy used for UA. Not only can food be grown on the available farmland, but it can also be used as an energy source by producing biofuel. This of course means again a reduction of Food availability.

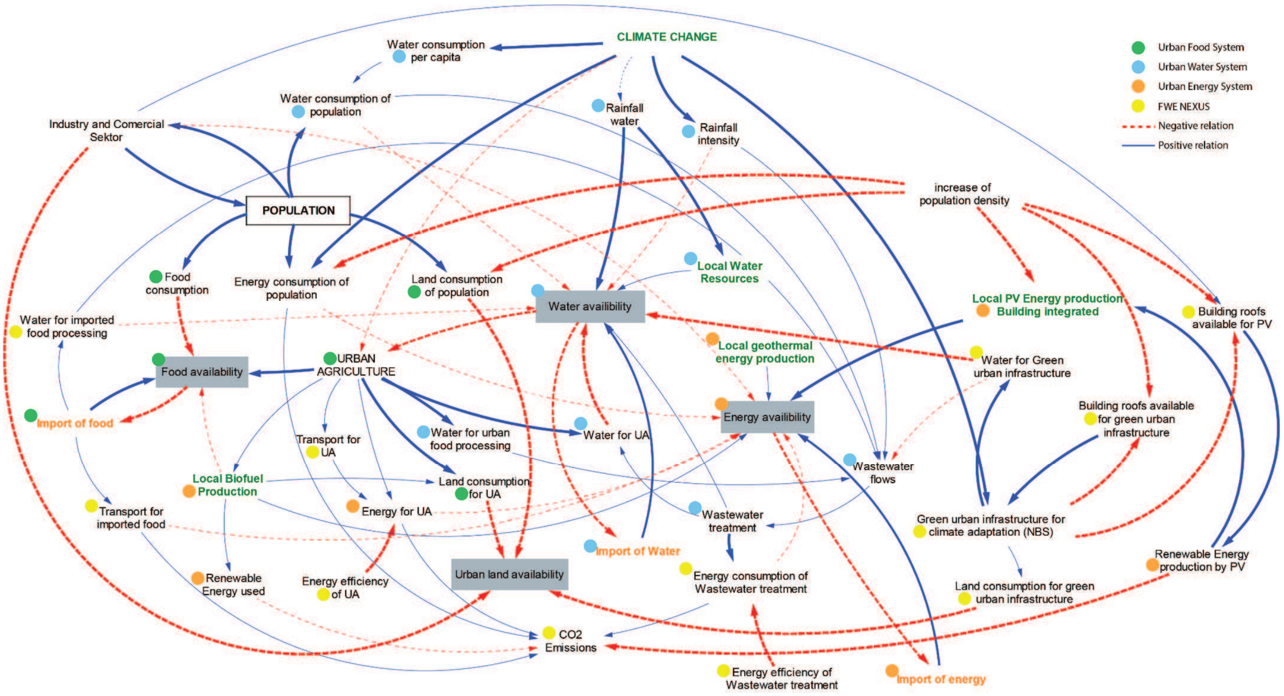

Fig. 1: Specific Causal food-water-energy relations for Vienna. ©AIT

The urban food production system is obviously closely related to the availability of urban land which creates conflicting interests. The main conflict due to population growth arises between urban food production and the construction of new dwellings and industrial areas including green urban infrastructure (e.g. parks). As construction activity for housing and industry increases, the availability of arable land decreases. Innovative forms of UA as vertical farming and aquaponic reduce this conflict but are currently not in the scope of the city of Vienna. To minimize the land consumption of the assumed population growth, the population density could be increased too (e.g. by increasing the building height). This would result in a decrease of the Land consumption of the population and might subsequently result in increased Urban land availability.

Another parameter that needs to be involved as a key impact factor in the future urban food production system is Climate Change. More than almost any other sector, agriculture depends on climatic influences. Even slight changes in temperature and precipitation have a noticeable impact on the level and annual variability of yields and agricultural incomes. Both in past and future growing seasons, heat waves result in dry and dusty fields and an unbalanced distribution of precipitation severly affects the agricultural yields (Mitter et al., 2014; BMLRT(a), 2019).

3.1.2 Urban Water System

Climate Change has also an important effect to the water availability. Increased Rainfall water would increase the local Water availability, whereas current climate models for Vienna make it very difficult to estimate the changes in the amount of rainfall. The Rainfall intensity is, according to the current climate models, easier to predict and will increase. This would increase the Wastewater flows and reduce the Water availability because the total amount of rainwater could not be stored by the environment – soil, lakes etc. – (the surface runoff will increase). Additionally to the more frequently occurring heavy rainfall, the climate models are predicting that heat stress/heat waves will also occur more frequently in the future. One of Vienna´s strategies to cope with this problem is to increase the green and blue urban infrastructure (e.g., on bulding roofs and facades or urban places (MA18(a), 2015)) which results in an increase of Water demand for Green urban infrastructure but will further reduce the Water availability due to the required irrigation needs. In general, the current water system for Vienna regarding drinking water and water for industry is

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dominated by water import from outside of Vienna and a growing population will further increase the need for more imports to the system.

3.1.3 Urban Energy System

The energy system of Vienna is currently dominated by energy imported to the system. Almost 90 % of the energy consumed in Vienna is imported (MA20, 2019). In the future a higher share of renewable energy produced within the city as well as a more efficient use of energy is key to meet the 2050 targets regarding the reduction of CO_2 emissions. Energy efficiency in urban agriculture aims e.g. at increasing the utilisation of waste heat from other uses for example to heat the green houses during winter season. The above-mentioned conflict for urban land and the possible mitigation strategy to use vertical farms would increase the amount of energy needed to grow the plants in these facilities. The source of this additional energy demand is decisive. Photovoltaic (PV) systems producing electricity on the roofs of the vertical farms would for sure be a starting point to tackle the energy demand, especially during the winter season. In general, increasing the amount of building integrated PV is part of the Smart City framework strategy for the future (MA18(b), 2019).

The population growth resulting in an increased population density would also decrease the Building roofs available for either PV or green urban infrastructure due to limitations of urban land availability and the construction of high-rise buildings (which could affect the solar radiation). Thus, a more vertical development of Vienna (like New York City) would also have negative side effects on other resources (Renewable energy from PV) due to limited space availability for the installation of the necessary infrastructure.

Another important Nexus connection related to the water system is the Energy consumption of Wastewater treatment which will increase with the population growth. An increase in the Energy effciency of Wastewater treatment would decrease the energy needs. The increased amount of treated wastewater could be used in Urban Agricuture (UA) and increases therefore the Water availability in the system.

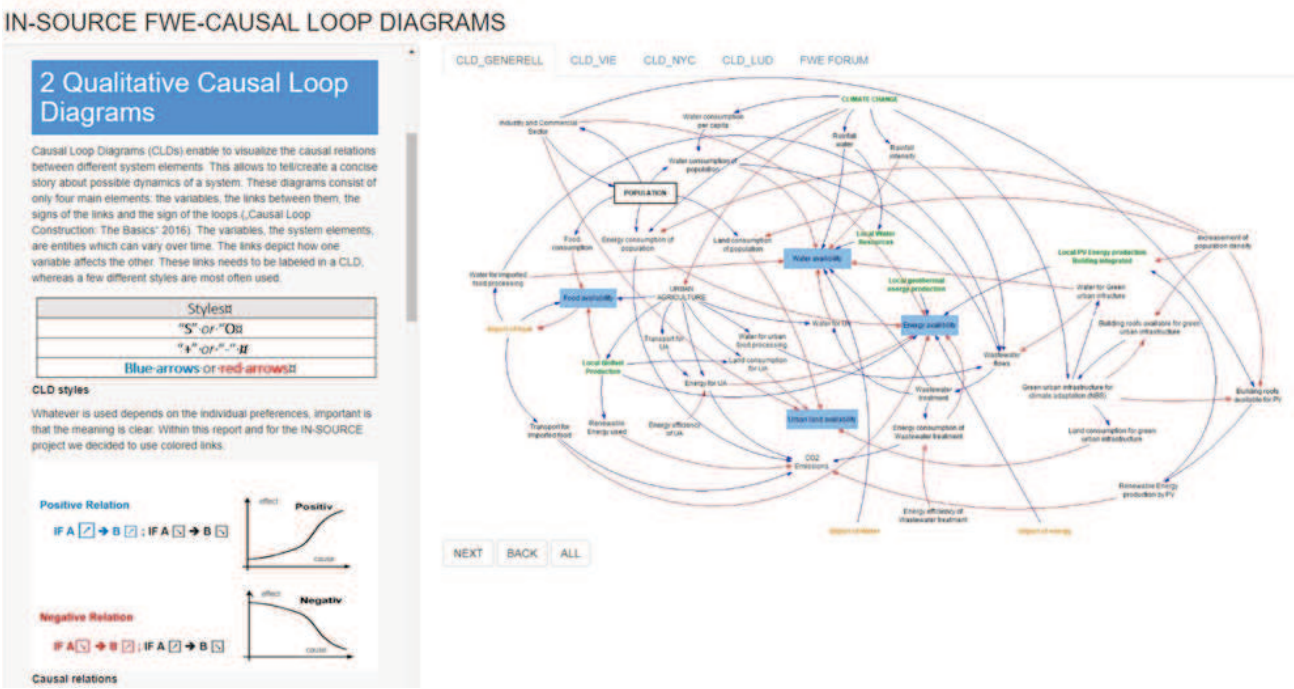

Fig. 2: Screenshot of the web-application to discuss the FWE-System – Specific CLD for Vienna, ©AIT

3.2 Story telling with CLDs

These causal relations discussed so far are only a part of the relations presented in the CLD (Figure 1). The aim was to present the use of the developed specific CLD to "tell a story" on what would happen if some of these causal relations would change (increase or decrease). During the discussion with the stakeholders (energy experts, urban planners, food related NGOs from Vienna) in the workshops, the CLD has been very valuable as the experts found important connections of their own domain to others and missing interrelations could also be identified by the experts which improves the entire system knowledge. As Figure 1 shows, CLDs are often very complex in the sense which makes it difficult to follow and analyse. To increase the usability, a step by step introduction is recommended. For this purpose we developed within the IN-SOURCE project an interactive web-application to help users to understand the contex more easily by telling the story.

Figure 2 shows a screenshot of this interactive web application (AIT(a), 2020). For the other case study regions, that are considered in IN-SOURCE, New York City (NYC) and Ludwigsburg specific CLDs were also created, which also can be found in the web-application.

4 QUANTITATIVE ANALYSIS

As mentioned above, based on the qualitative FWE Nexus system analysis, a quantification for important causal relations was performed. Main part of this was a GIS-based water demand analysis for different land use categories in Vienna. As basis, the current land use in Vienna, as shown in the following Figure 3, was used. The map illustrates the spatial distribution of urban agriculture-related land use categories in the city of Vienna in the year 2016. The map was created using open-source data supplied by Open Government Data Austria (OGD, 2019).

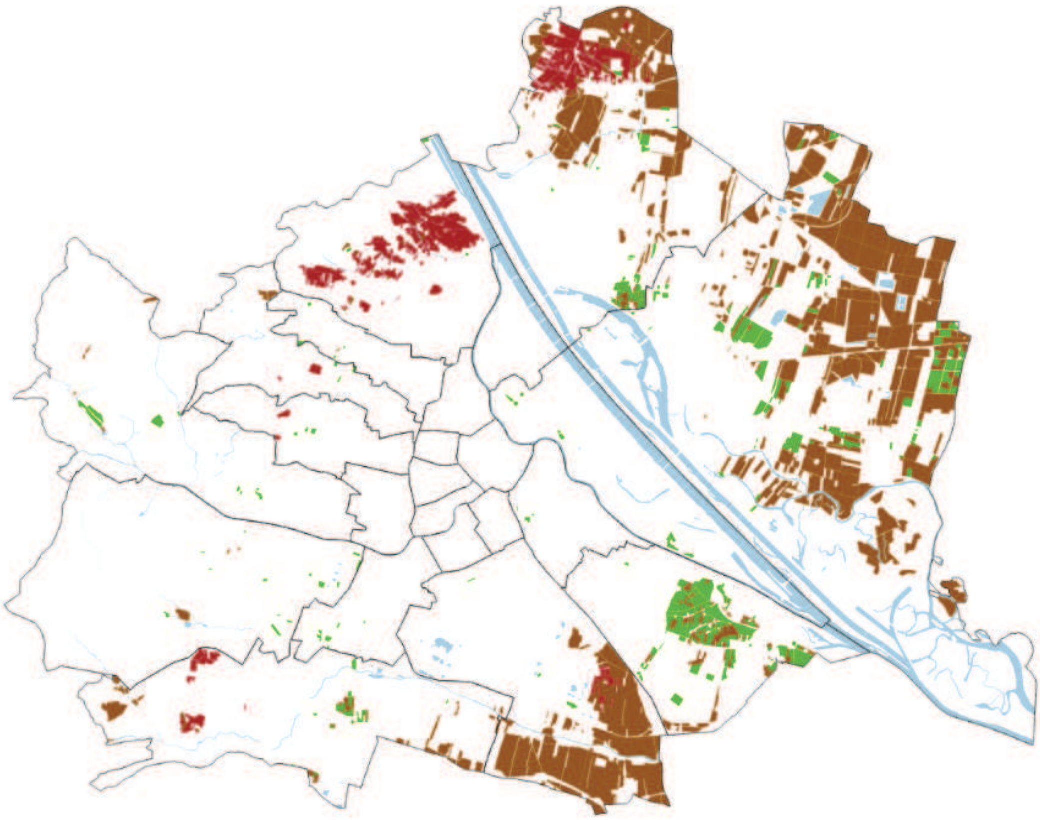

Fig. 3: Agricultural areas in Vienna 2016 (OGD, 2019), incl. water bodies and district boundaries of Vienna, ©AIT

There are 31 land use categories provided in the data set (OGD, 2019), while for this paper only so called “Urban Agricultural Areas” are of interest. These areas are divided into the three categories farmland, vineyard, nursery and orchard which cover 14% of the total area of Vienna. Farmland is most important because of the large proportion of urban agricultural area it occupies. Arable farming is mainly operated in the north, east and south of the city. Farmland corresponds to about 10% of the city’s total area, which is significantly higher compared to e.g. 4% of agriculturally used area in Berlin. (UBA, 2019).

In 2016 almost 38,000 tons of field crops (grains, oil fruits, pulses, potatoes) have been cultivated on about 3,000 ha arable land (used for cultivation of field crops) in Vienna. Wheat accounts for around 50% of the total harvest. Nevertheless the level of self-suffiency for Vienna within these products is rather low – about 8% self-sufficiency for grains (Landwirtschaftskammer Wien, 2017). Table 1 gives an overview of the per capita consumption of different foods in 2017/18 for selected products.

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Vegetables		**Grains**		**Others**	
	[kg/capita]		*[kg/capita]*		*[kg/capita]*
Tomatoes	29.0	Wheat	63.3	Sugar	33.3
Onions	9.4	Barley	0.5	Potatoes	49.0
Carrots	9.1	Maize	13.4	Legumes	0.9

Table 1: Per-capita consumption July 2017 to June 2018 of main foods in Vienna in kg (Statistik Austria, 2019)

For estimating the water demand for farmland, it was necessary to estimate the water demand of different field crops. For our approximation we used potatoes, tomatoes, wheat and sugar since they correspond to the biggest amount of herbal foods consumed per capita in Vienna. Thus, these crops were considered to simulate the water demand of the land use category farmland. For the calculation of the water demand of these crops, the simulation tool AquaCrop by FAO was used (AquaCrop FAO, 2019). AquaCrop is a crop growth model developed by FAO's Land and Water Division to address food security and assesses the effects of the environment and management on crop production.

AquaCrop uses the input parameters climate, crop information, irrigation and soil to calculate the water demand of certain crops. The crops wheat, tomatoes, potatoes and sugar beet chosen for Vienna were already implemented as default files in the simulation tool. Thus, it was only necessary to make adjustments regarding sowing and harvesting time for the considered crops according to common practice in Austria (Agrana, 2019; Laendle - Kartoffel, 2019; Vereinigung der Pflanzenzüchter und Saatgutkaufleute Österreichs, n.d.). It should be noticed that AquaCrop calculates the water demand for crops that are cultivated in open field production. In the case of tomatoes in Vienna, the results could differ from the real situation as the tomatoes are mainly grown in greenhouses. Since the per capita consumption of tomatoes in Vienna is rather high, the water demand of tomatoes nevertheless was simulated with AquaCrop, as a first approximation.

The software simulates the irrigation requirement for optimal crop development. This means that the plants are always supplied with sufficient water, naturally via precipitation or by additional irrigation, so that the plants do not suffer from water stress and can therefore develop optimally. Chernosem was defined as soil type, which is a common and suitable soil type for agriculture in Vienna (MA22, 2019; ViennaGIS, 2019).

For the simulation of Viennese crops, the local climate is of great importance. Climatic data provided by AIT (supported by high resolution dynamic simulations carried out with the regional climate model COSMO-CLM (AIT(c), 2019; Cosmo, 2020)) was used for present as well as for future climate. Therefore, it was possible to simulate the water demand of agricultural crops in the future. Table 2 illustrates the development of the average water consumed by typical Viennese crops in the climatic periods 2019-2048 (P1), 2049-2078 (P2), 2079-2098 (P3). Climatic periods were used to reduce the annual fluctuation in precipitation. The calculated water demand presented in the table below considers only water consumed by the crop growth. Water consumption for transport, processing or washing, etc. is not included.

	Water demand in mm/m²				
	P1: 2019-2048	P2: 2049-2078	Change (P1 to P2) [%]	P3: 2079-2098	Change (P2 to P3) [%]
Tomato	885	900	+1,7%	920	+2,2%
Spring wheat	1235	1265	+2,4%	1335	+5,5%
Sugar beet	1225	1235	0,8%	1245	+0,8%
Winter wheat	780	810	+3,8%	980	+21,0%
Potato	1045	1075	+2,9%	1145	+6,5%

Table 2: Development of the average total water demand of typical Viennese crop plants due to climate change

Although there is only little difference in total average water demand, the figures don't reveal the sources of water. As the changes show, the water demand remains rather constant for all considered crops except for winter wheat. However, there is a current trend towards increased winter wheat cultivation, which Austrian farmers are following. According to the Federal Ministry of Agriculture, Regions and Tourism (BMLRT), the cultivation of spring wheat is declining due to climate change and the resulting hot and dry summer months (BMLRT(b), 2019). Statistical data confirms this trend: From 2016 to 2019 the cultivation area for spring wheat declined by 57 % (2016: 101 ha; 2019: 43 ha) in Vienna (Statistik Austria(b), 2020).

To understand this trend, it is necessary to reflect upon the sources of water – from irrigation or precipitation – as mentioned above. Figure 4 seperates the sources of water into precipitation and irrigation for the same time period. It should be noticed, that the following figure exclusively shows water which is actually consumed and therefore necessary for plants to grow. The diagram shows the trend that in future the share of irrigation will increase continuously for all selected crops. Since all crops have different growing periods, the amount of precipitation, which can be used, differs. The best example is spring wheat and winter wheat. Whereas spring wheat is sown in spring and harvested in autumn, winter wheat is sown in the beginning of autumn. That is one of the reasons why the proportion of natural and water from irrigation differs between these two crops. Due to changing climate conditions, the distribution of precipitation during the year is shifting and can also be a reason for having to adapt the crop types.

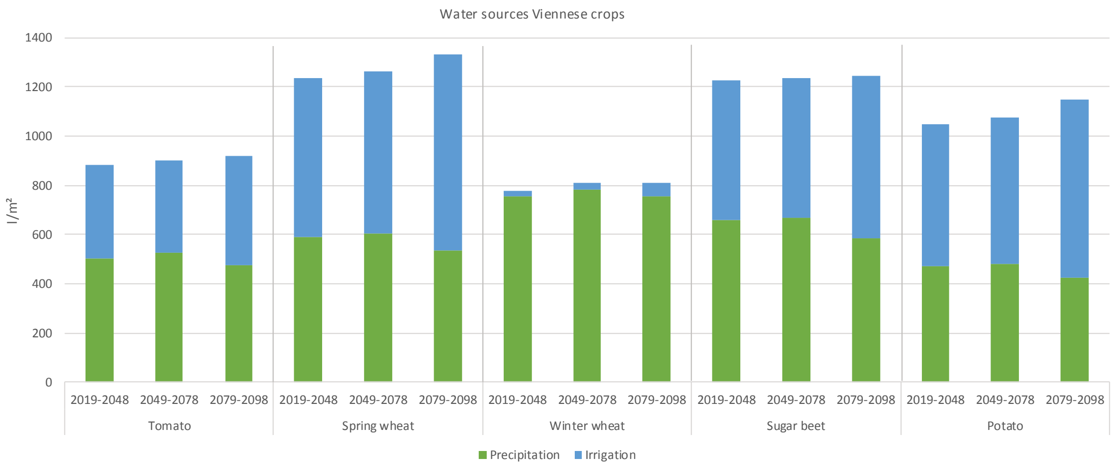

Fig. 4: Development of the average precipitation and irrigation requirement of typical Viennese crops 2019 to 2098, ©AIT

Focusing on spring wheat, the diagram illustrates that the irrigation requirement is sigificantly increasing: in the climate period 2079-2098, the proportion of irrigation will even be greater than that of natural precipitation. This development contributes to the conversion of the cultivation of winter wheat in Austria, as mentioned above. Whereas irrigation requirement represents the main share of the total average water demand for most of the considered crops, the share of irrigation requirement for winter wheat remains relatively low. The following figure 5 shows the monthly mean temperature and precipitation for the respective climate periods to compare the results with climate data.

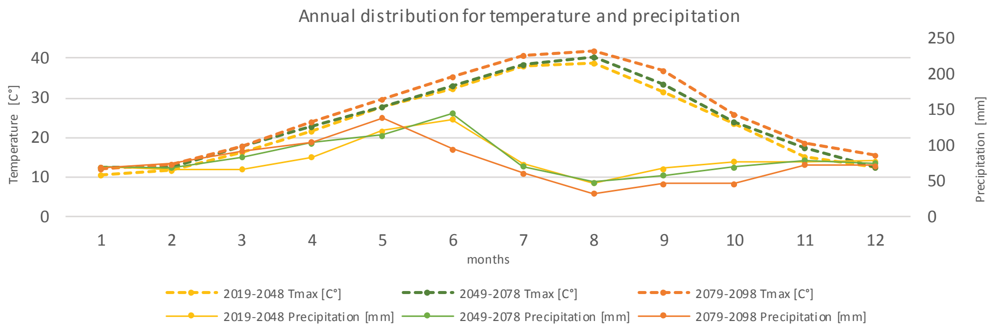

Fig. 5: Development of the monthly mean temperature and precipitation averaged over a 30-year span representing a time period from 2019 to 2098, ©AIT

As can be seen in the diagram, precipitation is steadily decreasing over time which is reflected in the irrigation demand for the considered crops. The climate model predicts a significant decrease of about 6% of precipitation for the period 2079-2098 compared to the previous period 2019-2048, as one factor leading to the required irrigation demand for the crops. In addition, the diagram shows an higher increase in temperature in the considered period during the entire year, which also increases the need for irrigation. The results of the climate model provide an outlook into the future, enabling to estimate the impact on the water demand for urban agriculture, in order to adapt to climate change. In summary, the results of the climate model show that a change is imminent in the next decades which will definitely influence the handling of resources.

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As part of the IN-SOURCE project, these analyses shall lead to an estimation of water demand for Vienna, based on land use categories. In this context, additionally to the water demand for arable land, water demand factors have been investigated within the project for all relevant land use categories.

The research has shown that currently only limited (publicly available) data on water consumption in Austria, especially in Vienna, is available for different land use categories, or is difficult to obtain. For the residential category, an average daily water consumption of 130l/(capita*day) was used (wien.gv.at, 2019), whereby this was in turn divided into several density categories as distinguished in real use (OGD, 2019) (e.g. dense residential area, garden city, large-volume residential construction, loosely built residential area/single-family houses area), as the water consumption in these housing options differ considerably from one another (Neunteufel, 2010). For industrial, commercial and service-oriented areas, estimating the water demand is difficult due to several parameters. According to Neunteufel, 2010, on the one hand, there are no figures on what proportion of Austrian industrial companies cover their water needs from the public water supply and what proportion is covered by self-supply (e.g. from ground water). On the other hand, the processes in industry/trade are very heterogeneous, which makes it difficult to estimate on a general level. In the commercial sector, values are usually set which, depending on the commercial enterprise, are multiplied by the number of employees or the quantity produced in order to take account of the different consumers. Nevertheless, there are some data that was collected from different studies and used in the project.

	Land use category	Mio.m³/a
Infrastructure	Industry & Service	46
	Social Infrastructure	7
	Mixed use	3
	Streetscape	3
	Technical Infrastructure	1
	Total:	60
Residential	Residential & Mixed use	66
Agriculture and Natural area	Recreational and leisure facilities	21
	Agriculture	30
	Natural area	49
	Total:	100
Total		226

Fig. 6: Water demand by land use categories, ©AIT

The results of the water demand analyses show a total water demand of 226 Mio. m³ per year in Vienna (calculation base year 2018). The residential use accounts for the largest share. The average water consumption for industrial/commercial areas was calculated at approx. 31,000 m³/ha and year, the agricultural and natural areas are estimated to consume an average of 5,000 m³/ha per year, which corresponds to about 1/6 of the demand of industry. For residential areas, between 2,000 and 19,000 m³/ha and year are needed, depending on the density of the residential area.

5 SUMMARY AND OUTLOOK

The aim of the qualitative approach using CLDs to highlight important FWE relations was to get a more appropriate view about the most relevant interactions. And indeed, the multiple connections give an idea of the complexity of the topic. The specific quantitative GIS-based analysis of land use changes and resulting water demand has shown, that there is further need for research activities in this area. The influencing factor of climate change concerning the change in water consumption needs to be investigated in more detail. Besides climate change, many other factors need to be taken into account, but cannot be assessed and truthfully projected into the future due to unpredictable trends. For example, changes in lifestyles like dietary habits are difficult to foresee. Scenario simulations can at least help to prepare for different possible futures and enable to create adquate adaptation measures.

Another research question that was raised in the project deals with the topic on how do new forms of urban agriculture (vertical farming, insect breeding, aquaponics) affect the specific water and energy consumption? Besides that, the development of green and blue infrastructure will also become a crucial topic in the future in order to accelerate climate change adaptation and benefit from the positive cooling effects to improve quality of life and well-being of citizens.

Our analyses has shown that still high uncertainties exist, but this first estimation enables to get an idea of the most important leverage points to influence the water balance and existing FWE Nexus relations. The next steps in the project are to use the first results to simulate a future water demand using input data from the climate model. These results will be used as input for the simulation model URBANICA (Gebetsroither, 2014; Gebetsroither, 2015; AIT(b), 2020) which enables the user to analyse the impacts of spatial planning scenarios for the sustainable management of resources. The aim is to support urban planners in creating climate resilient cities and regions with regards to the FWE aspects.

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