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Sustainable water use: spatioregional potential and limitations for the economy of Ukraine

Abstract. Introduction. Spatioregional gaps in water abundance, water productivity and use structure within the economy of Ukraine are studied insufficiently. Combined with the overall water insecurity and increased reliance on groundwater, these gaps limit the sustainability prospects and require strategically designed water policy approaches.

The purpose of the paper is, firstly, to identify the sustainable production possibility frontier with respect to water use, abundance and spatial competition for water resources for the national economy of Ukraine; and, secondly, to identify economic and governance risks associated with the existing spatioregional productivity gaps, and their policy implications.

Methodology. It is possible to identify the multi-dimensional national production frontier with land and water resource abundance being limiting factors. The position of the national economy under the frontier is described by the water use volumes in industry and agriculture. The maximization problem for the total output in the model provides, under certain assumptions, the realistic estimate of the economy's output potential, as well as the qualitative classification of the regions by their current position relative to the sustainable output potential. That is why, generalized water ecosystem protection scenarios developed in the literature were applied to establish the water use restrictions at 10% of the local water abundance at the regional and the national level, both for surface water and groundwater, and the waste water volume restrictions at 80% of the local water abundance. The resulting restrictions constitute the strongly sustainable water use volumes.

Results. The estimated sustainable GDP potential has only improved marginally for the 2018 data set compared to the average 2007-2011 data set, from USD 448.7 to 467.9 billion in nominal prices, suggesting lack of sustainability-contributing structural changes despite the drastic reduction in the observed water use in 2012-2018. The coefficient of agricultural output increase at the production frontier is equal to 0.89 for the 2018 model solution. This is the alarming result, suggesting highly unsustainable agricultural water footprint, which has been one of the reasons caused the generally lower sustainable GDP frontier value. Therefore, water limitations can be regarded even more relevant for sustainable development prospects compared to the well-known energy-related issues.

The qualitative classification has identified two groups of regions. The first group faces the major economic risks of insufficient water supply, but should not divert excessive resources towards hedging those risks. The second group has risks of future inefficiencies, and turns out to be additionally groundwater-reliant. While no conclusions pertaining to any particular region can and should be made based on the presented model, which is essentially nation-level, it outlines the potential regional risk profiles of the sectorial investment strategies and the related environmental, budgetary and political conflicts.

Conclusions. Our results call both for stronger uniformity and higher adaptivity of the water policy and management frameworks. The legislative basis should be improved for efficient participation and stronger links between the basin management plans and enforcement of water use and efficiency requirements. Further research should include development of a strong multi-level institutional framework for participatory water management, assessment of administrative and economic instruments within the context of river basin management, and studies of public-private clustering in water use.

Keywords: Water Productivity; Water Use; Production Possibility Frontier; Agricultural Water Footprint; Spatioregional Gap; Administration Conflicts

JEL Classification: Q25; Q56; Q15; R58; C61

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Стале водокористування:**просторово-регіональний потенціал та обмеження для економіки України**

Анотація. Просторово-регіональні диспропорції у водозабезпеченості, продуктивності води та структурі водокористування суттєво обмежують перспективи сталого розвитку в економіці та вимагають адекватних підходів на стратегічному рівні водної політики. На основі багатовимірної моделі межі виробничих можливостей з обмеженнями обсягів регіонального водокористування в статті оцінено потенціал сталого виробництва в національній економіці та виявлено потенційні ризик-профілі для регіонів України з огляду на секторні інвестиційні стратегії та можливі екологічні, бюджетні та політичні конфлікти. Надано рекомендації відносно вдосконалення інституційного забезпечення водної політики щодо участі зацікавлених сторін, вирішення конфліктів та регулювання господарської діяльності.

Ключові слова: вода; продуктивність водокористування; межа виробничих можливостей; водний відбиток сільського господарства; просторово-регіональні диспропорції; адміністративні конфлікти.

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Устойчивое водопользование:**пространственно-региональный потенциал и ограничения для экономики Украины**

Аннотация. Пространственно-региональные диспропорции обеспеченности водными ресурсами, продуктивности воды и структуры водопользования существенно ограничивают перспективы устойчивого развития в экономике и требуют адекватных подходов на стратегическом уровне водной политики. На основе многомерной модели границы производственных возможностей при ограничении объемов регионального водопользования в статье оценен потенциал устойчивого производства в национальной экономике и выявлены потенциальные риск-профили для регионов Украины с учетом секторных инвестиционных стратегий и возможных экологических, бюджетных и политических конфликтов. Даны рекомендации по усовершенствованию институционального обеспечения водной политики для участия заинтересованных сторон, разрешения конфликтов и регулирования хозяйственной деятельности.

Ключевые слова: вода; продуктивность водопользования; граница производственных возможностей; водный отпечаток сельского хозяйства; пространственно-региональные диспропорции; административные конфликты.

1. Introduction

Water insecurity of the national economy is a well-known fact (Romaschchenko et al., 2015; Yara et al., 2018); however, relatively little attention is paid to it particularly in the economic literature, as compared to the issues of energy efficiency, air pollution and land use. Water use in Ukraine has shifted dramatically over the past decade. The withdrawal amounts have shortened by nearly one third since 2011 to 2018, from 15.2 to 10.7 billion cubic meters annually, including surface water and ground water withdrawal; however, reliance on groundwater increased in some regions, exposing society to more environmental risks (Melnychuk et al., 2012; State Statistics Service, 2019a). Moreover, the dominant share of transitory flows, as opposed to the own water resource, which constitute 75% of total water abundance, as well as the long term supply risks, measured by fluctuations in annual water balances, which constitute more than 60% (Ministry of Environment, n.d.), exacerbate the risks related to climate change and foreign nations' water management.

Energy sector, irrigation and heavy industries are the primary water users in Ukraine (Melnychuk et al., 2012); large shares of natural flows redistribution make the economy water-dependent. This limits the prospects of sustainable economic growth and raises the question of quantitative estimation of sustainable productive potential of water resources. While sectorial restructuring and resource efficiency innovations constitute the obvious requirement for transition towards sustainability (Grobicki, 2008), the sustainable water use capacity of the existing territorial economic structure, and the related spatioregional implications of water vulnerability, require special approaches designed on the strategic level of the national water policy. This is due to sharp spatioregional differences in water abundance, productivity and use structure, which implies different regional as well as macro-level risk profiles and potential conflict sources. Economic analysis of Ukrainian river basins, including groundwater basins, is not available at the time, while comparisons of water footprint prevail in cross-country and macroeconomic

analyses (Panasiuk et al., 2018; Liu and Yang, 2010). For this reason, spatial aspects of water economy in Ukraine, as well as the related prerequisites of conflict resolution mechanisms design, can not be considered sufficiently spelled out in the literature.

The existing water management strategies and regulations, particularly in the European Union, pay close attention to conflict resolution. In Ukraine, strategic planning of water policy reform is currently presented by the Water Policy Strategy Green Book (Ministry of Environment, 2019) intended for wide discussion. The document presents an interregional conflict resolution framework constituted by Basin Councils as envisaged in the EU Water Framework Directive, as well as the nation-wide water policy forum. However, multi-level and multi-stakeholder participation mechanisms still need to be fleshed out efficiently to mitigate the conflict risks related to productivity gaps. On a more general level of treatment, the necessity of such mechanisms stems from spatiality of sustainability issues, including the conflict-prone governance of biospheric capital (Hryniv and Khodyko, 2018). These considerations define the urgent policy relevance of the topic.

The research goal of the paper is to contribute to discussion of water policy and management strategy for Ukraine by pointing towards requirements for multi-regional and multi-stakeholder participation mechanisms motivated by nation-wide sustainability risks of spatioregional water abundance. The research tasks are to estimate the existing limitations to sustainable production related to water use efficiency and patterns, using the sustainable production possibility frontier modelling, as well as to identify the economic risks, conflict sources, and policy implications related to the water productivity gaps in the economy.

Our starting point is the concept of water productivity, structurally similar to the widely applied concept of GDP energy intensity. While the average water productivity measures between 2012 and 2018, which limit the period of study, reflect multiple region-level shifts, the overall nation-wide trends require an integrated production frontier model. Changes in productivity, caused by shifts in sectorial structure and technological profile move the frontier itself; at the same time, the spatio-regional distribution of production and water use identifies position of the national economy under or at the frontier. For purposes of dynamics estimation for an otherwise static model, we have used two model coefficient sets, based on the 2012 and 2018 statistical data. Restrictions imposed in the model reflect estimations of sustainable volume of water use, based on the national water footprint framework (Hoekstra, 2014), which allows identifying norms of water use in production, as well as waste water volumes. We are using the latest available data on the regional and nation-wide water balance, which is updated on the long-term basis (Ministry of Environment, 2017). This allows and requires attributing the differences between the model outcomes for the two data sets entirely to structural and technological factors.

Using the water-restricted production possibility frontier modelling, we have identified, first, that Ukraine may have deteriorated its structural and technological potential, particularly in the agricultural sector, during the period of study. This is indicated by the approximately constant production possibility frontier and the according values of sustainable water use-based GDP potential for the 2018 compared to 2012. Moreover, the estimated GDP potential values imply the per capita product lower than the current actual values for the more developed countries of the Central and Eastern Europe. Second, the model, while not being intended for any region-level conclusions, has identified two possible regional-level risk profiles characteristic for regions on the basis of their sectorial structure, hydrogeographical position, water abundance and relative contribution to the national economy, unlike the previous studies, which indicate no pronounced spatial differences in water efficiency within the national economy.

The first profile includes the major economic risks of insufficient water supply; however, the respective regions should not divert excessive resources towards hedging those risks.

The second profile generally includes risks of future water inefficiencies, as well as environmental risks caused by increasing reliance on groundwater withdrawal. The regions of both risk groups are prone to conflicts of various origins, potentially involving the central governmental agencies in one way or another.

While we obviously admit the need for technology improvement and sectorial restructuring, the model implies a particular water policy scenario, based on the water use patterns and productivity, which envisages the «optimistic» extent of investment into the existing («conservative») water use patterns, technologies and production, with a reactive stance towards sustainability. Moreover, the model presents an arguably «optimistic» estimation of productive potential with respect to diminishing returns and economies of scale. Generally, this results in an upper bound

estimation of the water-restricted GDP potential, and an overstatement of interregional water productivity gaps. Accordingly, sustainability issues should be emphasized when drawing policy implications, and the issues of the regions potentially «overutilizing» their sustainable production capacity, their risks of economic depression, as well as extensive water safety demands, should be of major strategic concern.

The paper is organized as follows. The section 2 reviews the literature, first, to discuss the treatment of water as a production factor and the joint application of water productivity and water footprint concepts for spatioregional assessment of sustainability prospects; second, to review global water policy challenges and trends, as well as institutional gaps; and, third, to briefly overview the existing contributions to water policy discussion in Ukraine. The section 3 states the research purpose. The section 4 consists of three parts, with the subsection 4.1 summarizing the patterns of water use and productivity dynamics in Ukraine to identify the requirements for the integrated water use modelling and the water policy scenario underlying the model. The subsection 4.2 describes the formal model and data, reports the relevant results and outcomes, as well as discusses the assumptions and interpretation of modelling estimations. The section 4.3 discusses the policy implications of the outcomes for Ukraine within the context of the Water Policy Strategy Green Book. The section 5 concludes by summarizing the findings and outlining directions for future research.

2. Brief Literature Review

The conceptual treatment of water in economic literature has faced the issues similar to the ones related to treatment of energy. Water as a material input not possessing an economic productivity in itself can be included into environmental economic considerations through the water footprint framework (Hoekstra, 2014). This approach has informed the a priori scenario-based normative amounts of freshwater withdrawal from surface sources (Richter et al., 2011) and groundwater stocks (Gleeson and Richter, 2017). Waste water treatment, on the other hand, is to be based on comparative water pollution amounts, and the corresponding grey water amounts (Bonamente et al., 2017). Vystavna et al. (2018a) provide an overview of Ukrainian urban rivers pollutants in comparison with the European Union levels, with the direct implications for estimation of the national grey water footprint.

Considering water a production factor, alongside the traditional ones as well as energy and raw materials, leads to the notion of water productivity, equivalent to «economic value» or «shadow price» of water (see Vasquez-Lavin et al., 2020 for the recent review). The relevance and application of water productivity is not unproblematic. Zobl (2006) has contrasted water productivity (defined as economic output value per unit of water consumed) with water efficiency (defined as non-valued product output per unit of water), arguing against the former as highly misleading and not reflecting water economy and use technology at least in the agricultural sector. Nevertheless, the concept has persisted in the macroeconomic context of sustainability management, being used recently to assess gross regional product impacts of water shortages (Zhan et al., 2015) and competitiveness impacts of water policy (Vasquez-Lavin et al., 2020), as well as to improve sustainability-related decision making by establishing economic value of water processed in biophysical systems, i.e. of «green water» (Grammatikopoulou et al., 2019). This kind of estimation is beneficial by moving beyond the macro-level equivalence of green water and land resources (Hoekstra, 2014) towards the more locally sensitive decision-making; besides, it exemplifies adoption of water footprint concept into economic studies. Zhan et al. (2015) depart from the input-output efficiency of water to obtain marginal water productivity values through scenario analysis in computable general equilibrium framework, therefore not assuming constant water productivities. Despite the single-region scope and spatially insensitive modelling, their approach shows how water productivity differences may reflect interregional structural and technological disparities. Unlike the abovementioned studies, Zhao et al. (2019) use the average rather than marginal water productivity values to identify factors of regional trade specialization. While their results downplay the importance of water productivity as a comparative advantage factor of both water-deficient and water-abundant regions, the policy implications call for tight integration of water policy with sectorial and structural issues of the regions and the country as a whole.

Water productivity is widely available for cross-country comparisons on macroeconomic level (Grobicki, 2008; Panasiuk et al., 2018), as well on sectorial level, particularly in agriculture

(Zwart et al., 2010). Vasquez-Lavin et al. (2020) additionally provide a survey of water price elasticity estimations available in the literature, which, according to them, reflects potential competitiveness impact of water policy, although the direct comparison is hardly possible given the differing estimation contexts and methodologies. The region-level water footprint and productivity estimations are available for different countries (Bonamente et al., 2017; Zhao et al., 2019). The wheat water productivity benchmarks spatially assessed on the global scale (Zwart et al., 2010) display no apparent spatial difference within Ukraine, with the exception of Crimea and the bordering Kherson region. The estimates of agricultural water consumption have shown difference between the northwestern regions of Ukraine, as well as Transcarpathian region, and the rest of the country, which has rather high consumption levels on European scale (Liu and Yang, 2010). Given the previously identified difference in water-related productive potential within the territory of Ukraine (Rudenko et al. 2014) and the prominent over-specialization of the regions (Melnyk et al., 2012), the spatioregional distribution of productive potential and sustainability limitations related to water use, particularly taking industrial water efficiency into account, deserves further attention due to prevalence of industry-related water users in the Ukrainian economy. Climate change has stimulated water policy reforms and experiments across the world in recent decades. While the climate change impact on water quantity can be ambiguous and even lead to its increase, particularly for large navigable rivers (Christodoulou et al., 2019), such impact in general is distributed unevenly across communities and social groups (Tsegai and Bruentrup, 2019; Dilling et al., 2019). The analysis of drought impacts in the UK (Parsons et al., 2019) suggests that the widespread drought measures should be interpreted on the regional rather than national level while taking the climate and agricultural differences into account, with the similar logic for water policy implications. These findings require particular attention towards water use rights allocations, in national as well as transboundary contexts. Many water-deficient states have shifted from exclusively water redistribution measures to a risk-based conservation approach, including the economic instruments of market-based rights reallocation. Although environmental considerations play a secondary role in these policy reforms, groundwater access is heavily regulated and mostly separated from land ownership (Berbel et al., 2019). Meanwhile, the established water rights markets remain mostly underdeveloped, with mixed results depending on the exact definition of water rights (Dilling et al., 2019). Such entitlement definitions are often rooted in the historical context. This is the case with the «Colorado doctrine» of public water ownership administered through use rights allocations (McLeman, 2019), where historical allocations against the shifted demand have created incentives for land rights misuses and resulted in rural decline. On the other hand, the doctrine of public water benefits with its legal interpretations is itself based upon the institutional traditions and therefore may have its own limitations in sustainability management and environmental protection context (Cantor, 2016). This may turn out relevant in Ukrainian context due to the widely quoted constitutional provision on public natural resource ownership. Due to this institutional sensitivity, development of water rights markets remains a general challenge worldwide (Berbel et al., 2019).

The ongoing water policy reform in Ukraine is considered incomplete despite the introduction of River Basin Management principles, as required by the European Union's Water Framework Directive into the Water Code, and the adoption of a number of subordinate regulations. The literature identifies the general vagueness of regulatory norms (Dombrowsky et al., 2014), fundamental differences between socioeconomic and ecosystem-based paradigms prevalent in the Ukrainian and the European policy design (Vystavna et al., 2018b), and low efficiency of environmental economic instruments in place in Ukraine for tackling water management issues (Yara et al., 2018), as the major directions for improvement and capacity building. Groundwater management requires particular attention on both national and pan-European level (Ladychenko et al., 2019). The governmental perspective of water policy strategy (Ministry of Environment, 2019) has not yet incorporated a number of strategic instruments and participation mechanisms identified by previous research (Romaschchenko et al., 2015), including the possible frameworks for participatory water policy scenario development on various levels (Zhovtonog et al., 2011), but nevertheless provides the ground for comprehensive policy formation. Particularly, the spatial dimension of water policy, founded upon the River Basin Management principles, needs to be efficiently coupled with the changing role of territorial communities and the forming multi-level governance in Ukraine for further contribution towards sustainability.

3. Purpose

The paper aims to contribute to water policy discussion in two directions. First, we aim to identify the sustainable production possibility frontier, with respect to water use, abundance and spatial competition for water resources, for the national economy of Ukraine. Second, the model outcomes make it possible, while obviously admitting the necessary restructuring and technology improvement, to identify economic and governance risks associated with the existing spa-tioregional productivity gaps, and their implications for comprehensive national water policy and management strategy.

4. Results

4.1. Water use patterns and productivity in the national economy

Water use has decreased by nearly one third in the economy of Ukraine over 2012-2018, as Table 1 shows. The economic decline, industrial restructurization and armed conflict may be listed as potential causes of this kind of dynamics. However, while surface withdrawal has undergone the reduction, groundwater withdrawal volumes have changed little in many regions, which reflected in major increases of groundwater shares in total withdrawal. Notably, the groundwater share has increased by 2.7 in Odesa region, by 2.4 in Kyiv region.

Real water productivity in industry, calculated as the total industrial output per unit of production-related water use, has increased by 11% in Ukraine over the same period, as shown in Table 2. In some regions, the increase has been prominent, reaching as high as 117% in Kyiv region. Productivity of waste water, calculated as the total industrial and agricultural output per unit of non-residential waste water, has increased by 2.34 in Poltava region, by 2.8 in Kirovohrad, by 1.9 in Rivne etc.

Table 1:
Water withdrawal structure in the regions of Ukraine, 2012-2018

	2012				2018					
	Surface water withdrawal, mln c.m.	Groundwater withdrawal, mln. c.m.	Total withdrawal, mln. c.m.	Ground-water, %	Surface water withdrawal, mln c.m.	Groundwater withdrawal, mln. c.m.	Total withdrawal, mln. c.m.	Ground-water, %	Changes in withdrawal	Groundwater share index (2012=base)
Cherkasy	226.25	59.65	285.9	21%	137	47	184	26%	-36%	1.2
Chernihiv	99.82	58.38	158.2	37%	84	44	128	34%	-19%	0.9
Chernivtsi	53.9	21.29	75.19	28%	46	21	67	31%	-11%	1.1
Dnipro-petrovsk	1522.68	181.12	1703.8	11%	1051	128	1179	11%	-31%	1.0
Donetsk	1749.84	397.96	2147.8	19%	1039	102	1141	9%	-47%	0.5
Ivano-Frankivsk	99.57	8.17	107.74	8%	90	6	96	6%	-11%	0.8
Kharkiv	304.16	48.74	352.9	14%	279	34	313	11%	-11%	0.8
Kherson	1123.95	68.05	1192	6%	2976	59	3035	2%	155%	0.3
Khmelnysk	114.2	51.36	165.56	31%	58	42	100	42%	-40%	1.4
Kirovohrad	111.92	28.62	140.54	20%	147	17	164	10%	17%	0.5
Kyiv	977.11	48.69	1025.8	5%	468	60	528	11%	-49%	2.4
Luhansk	135.42	370.24	505.66	73%	48	48	96	50%	-81%	0.7
Lviv	69.72	179	248.72	72%	28	144	172	84%	-31%	1.2
Mykolayiv	237.73	16.19	253.92	6%	219	13	232	6%	-9%	0.9
Odesa	2136.24	33.96	2170.2	2%	713	31	744	4%	-66%	2.7
Poltava	190.58	83.7	274.28	31%	41	73	114	64%	-58%	2.1
Rivne	148.87	48.09	196.96	24%	79	41	120	34%	-39%	1.4
Sumy	65.77	50.91	116.68	44%	49	43	92	47%	-21%	1.1
Ternopil	45.92	28.13	74.05	38%	25	26	51	51%	-31%	1.3
Trans-carpathian	16.4	30.72	47.12	65%	26	21	47	45%	0%	0.7
Vinnysia	104.13	20.43	124.56	16%	102	16	118	14%	-5%	0.8
Volyn	39.22	58.41	97.63	60%	16	53	69	77%	-29%	1.3
Zaporizhzhya	1136.38	52.1	1188.48	4%	1214	46	1260	4%	6%	0.8
Zhytomyr	183.36	21.74	205.1	11%	90	21	111	19%	-46%	1.8
Kyiv City	668.11	56.31	724.42	8%	515	29	544	5%	-25%	0.7
Crimea AR	1442.46	92.14	1534.6	6%	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sevastopol City	70.36	14.75	85.11	17%	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ukraine	13111.78	2098.14	15209.92	14%	9540	1165	10705	11%	-30%	0.8

Source: Author's own calculations based on data by The Ministry of Environment and Natural Resources (n.d.) and State Statistics Service of Ukraine (2019a)

Table 3 shows qualitative changes by compiling an industrial water productivity rating. Most of the regions preserved higher than the Ukrainian average productivity over the six year period, while the list of less productive regions remained unchanged as well. Dnipropetrovsk has moved above the Ukrainian average, while Luhansk and Donetsk lowered their position drastically. On the other hand, the highly productive regions (Lviv, Volyn, Odesa and Kharkiv) increase their productivity further. The productivity gap across the Ukrainian regions has therefore persisted and widened during the period in consideration.

The increase in productivity, however, is often accompanied by increased reliance on ground-water water withdrawal, as the data in Tables 3 and 1 indicate. Many of the regions having advanced in their productivity rating, including Volyn, Zhytomyr, Ternopil and Lviv, with the exception of Vinnytsia, have shifted towards groundwater sources, with the leading Poltava region having doubled its groundwater share. Odesa region has increased the share nearly threefold. This suggests that the productivity increases may have been caused by reductions in water-demanding industries relying on surface waters, and therefore, may not be scalable.

On the other hand, productivity reduction does not necessarily correspond to water use increase; in fact, Kherson has increased water use by 155% and productivity by 45%, while Donetsk case demonstrates the dismantled economy of scale, with almost uniform decreases of water withdrawal and productivity. It is thus unknown whether the water-extensive production shutdowns might contribute to average productivity increase, while new water-demanding productions might even contribute to productivity growth in some regions due to economy of scale.

The sustainability prospects are thus incomplete, and the macroregional analysis generally associated with much difficulty. The vast amounts of water redistribution in the national economy, with large differences between the proper water resource of the regions and the amounts available to their economies through transitory flows and redistribution, i.e. between the local and the total water abundance, contribute to the difficulty of analysis, while intensifying the economic, as well as political spatial competition for water resources in the economy.

Hence, for purposes of a macrolevel analysis, a general model is necessary to include both production potential and water resource potential within a multiregional environment. Based on the

Table 2:
Average water productivities in the regions of Ukraine, 2012-2018

	Water productivity in industry, UAH/c.m.			Waste water productivity, UAH/c.m.			CPI (2012=base)	Real productivity change	
	2012	2018	2018 (real)	2012	2018	2018 (real)		Industry	Waste water
Cherkasy	715.35	1013.69	438.14	272.31	1489.79	643.91	231.37%	-39%	136%
Chernihiv	182.96	493.04	209.28	330.10	830.93	352.70	235.59%	14%	7%
Chernivtsi	199.21	610.50	273.19	233.92	1375.09	615.34	223.47%	37%	163%
Dnipropetrovsk	200.14	751.98	328.69	241.08	972.51	425.08	228.78%	64%	76%
Donetsk	297.25	312.36	133.02	202.57	353.63	150.60	234.82%	-55%	-26%
Ivano-Frankivsk	371.35	1138.6	496.07	442.20	1766.32	769.56	229.52%	34%	74%
Kharkiv	660.84	1552.39	664.36	557.91	1213.27	519.23	233.67%	1%	-7%
Kherson	347.20	1180.43	503.04	481.16	1270.54	541.45	234.66%	45%	13%
Khmelnysk	440.94	1052.46	448.51	1786.83	2879.00	1226.90	234.66%	2%	-31%
Kirovohrad	1253.59	2100.61	934.15	902.88	7684.15	3417.17	224.87%	-25%	278%
Kyiv	61.98	308.80	134.54	85.08	375.84	163.75	229.52%	117%	92%
Luhansk	785.93	492.56	219.99	394.11	1002.67	447.81	223.91%	-72%	14%
Lviv	699.35	2401.19	1044.68	274.44	1149.12	499.95	229.85%	49%	82%
Mykolayiv	238.09	672.86	292.74	932.48	2098.12	912.83	229.85%	23%	-2%
Odesa	413.41	1638.40	678.12	237.85	1142.12	472.71	241.61%	64%	99%
Poltava	1347.14	5751.71	2437.26	747.04	7685.72	3256.78	235.99%	81%	336%
Rivne	139.79	567.50	242.31	200.24	1397.79	596.82	234.21%	73%	198%
Sumy	803.56	1460.45	623.57	1267.83	3552.46	1516.79	234.21%	-22%	20%
Ternopil	352.14	1240.92	529.84	333.04	1925.14	821.98	234.21%	50%	147%
Transcarpathian	1711.07	3224.62	1404.71	495.40	1368.18	596.01	229.56%	-18%	20%
Vinnytsia	350.68	1363.01	592.93	1044.69	2936.56	1277.44	229.88%	69%	22%
Volyn	508.14	2387.37	1035.91	937.10	4501.52	1953.27	230.46%	104%	108%
Zaporizhzhya	85.24	226.00	99.99	114.91	277.44	122.75	226.02%	17%	7%
Zhytomyr	326.33	1129.86	481.15	197.88	1264.81	538.62	234.82%	47%	172%
Kyiv City	556.71	1517.46	663.27	552.17	1265.18	553.00	228.78%	19%	0%
Crimea AR	314.64	n.d.	n.d.	283.84	n.d.	n.d.	n.d.	n.d.	n.d.
Sevastopol City	172.07	n.d.	n.d.	177.45	n.d.	n.d.	n.d.	n.d.	n.d.
Ukraine	266.06	676.86	294.44	272.87	820.63	356.98	229.88%	11%	31%

Source: Author's own calculations based on data by The Ministry of Environment and Natural Resources (n.d.) and State Statistics Service of Ukraine (2013, 2019a, 2019b)

Table 3:
Water productivity ranking of the regions of Ukraine, 2012-2018

	Rank (2018)	Rank (2012)	Change
Poltava	1	2	+1
Transcarpathian	2	1	-1
Lviv	3	7	+4
Volyn	4	10	+6
Kirovohrad	5	3	-2
Odesa	6	12	+6
Kharkiv	7	8	+1
The city of Kyiv	8	9	+1
Sumy	9	4	-5
Vinnitsia	10	15	+5
Ternopil	11	14	+3
Kherson	12	16	+4
Ivano-Frankivsk	13	13	0
Zhytomyr	14	17	+3
Khmelnysk	15	11	-4
Cherkasy	16	6	-10
Dnipropetrovsk	17	22	+5
Ukraine	18	20	+2
Mykolayiv	19	21	+2
Chernivtsi	20	23	+3
Rivne	21	26	+5
Chernihiv	22	24	+2
Luhansk	23	5	-18
Donetsk	24	19	-5
Kyiv	25	28	+3
Zaporizhzhya	26	27	+1
Crimea AR	n.d.	18	n.d.
The city of Sevastopol	n.d.	25	n.d.

Source: Author's own calculations based on data by The Ministry of Environment and Natural Resources (n.d.) and State Statistics Service of Ukraine (2013, 2019a, 2019b)

land and water productivity data, it is possible to identify the multi-dimensional national production frontier, with land and water resource abundance functioning as limiting factors and the position of the national economy under the frontier is described by the water use volumes in industry and agriculture. The maximization problem for the total output would provide the associated water distribution across the regions within the economy.

The economic sense of this kind of solution is bounded by one possible water policy scenario, which the above presented facts allow establishing. The scenario is essentially the «market first» option, according to Scales project framework, concerning the «optimistic» extent of investment into the existing («conservative») water use patterns, technologies and production, without any implications of best available technology utilization, and with a reactive stance towards sustainability. While these limitations of modelling premises are obvious, the impact of assumptions and relevance of some particular results obtained will be discussed below.

4.2. Modelling the spatioregional efficiency frontier of water use for Ukraine

The production frontier can be defined in n-dimensional space, with axes corresponding to regions' production outputs. All points on the frontier have the property of having a constant sum of water use, thus showing either sustainable or absolute limits. The substitution elasticity is imperfect due to regional water limits, so the frontier is a convex hypersurface, changing shape according to relative productivity changes across regions. The distance to the frontier from a given point corresponds to cross-region distribution of production within the national economy, which is assumed scalable with the corresponding production increase or decrease. With the residential and miscellaneous water uses, as well as the land-dependent agricultural output held constant, scaling of the national production can be modelled by multiplying the industrial and irrigation water use volumes of all regions by the single coefficient denoting the ratio of the total current water use to the total water use limit. The resulting model is linear by construction and is subject to the well-known numerical methods of solving. The solution to the linear maximization problem provides the maximum value of total production in the economy satisfying the resource constraints, with the corresponding values of regional outputs which, due to linear scalability and constant regional water productivity, allow obtaining the single cross-regional water use structure, optimal under the defined scenario and scalability assumption.

Formally:

$$O_N = \sum_{i=1}^n O_{R,i} , \quad (1)$$

where:

O_N - national output,
 $O_{R,i}$ - regional output of the i -th region;

$$W_N = \sum_{i=1}^n W_{R,i} , \quad (2)$$

where:

W_N - national water use,
 $W_{R,i}$ - regional water use of the i -th region;

$$A_N = \sum_{i=1}^n A_{R,i} , \quad (3)$$

where:

A_N - national total volume of waste water disposed,
 $A_{R,i}$ - waste water volume of the i -th region;

$$O_{R,i} = W_{IND,i} * P_{W,i} + \frac{W_{IRR,i}}{D_{IRR,i}} * P_{P,i} + L_{R,i} * P_{C,i} , \quad (4)$$

where:

$W_{IND,i}$, $W_{IRR,i}$ - industrial and irrigation water use,
 $P_{W,i}$, $P_{P,i}$, $P_{C,i}$ - productivities of industrial water use, land use in plant cultivation and total agricultural land use in cattle farming,
 $L_{R,i}$ - total agricultural land area of the i -th region,
 $D_{IRR,i}$ - irrigation water demand per unit of land in the i -th region;

$$W_{R,i} = W_{IND,i} + W_{IRR,i} + W_{RES,i} + W_{MISC,i} , \quad (5)$$

where:

$W_{RES,i}$, $W_{MISC,i}$ - residential and miscellaneous water use, held constant in the model, for the i -th region;

$$A_{R,i} = \frac{O_{R,i}}{P_{A,i}} + W_{RES,i} + W_{OTH,i} , \quad (6)$$

where:

$P_{A,i}$ - productivity of waste water disposal in the industry.

The maximization problem is then written as follows:

Let us maximize O_N subject to:

$$W_{R,i} \leq 0.1 * LWA_{R,i} , W_N \leq 0.1 * LWA_N , \quad (7)$$

where:

$LWA_{R,i}$ - local water abundance for the i -th region,
 LWA_N - local water abundance for the country;

$$A_{R,i} \leq 0.8 * LWA_{R,i} , A_N \leq 0.8 * LWA_N , \quad (8)$$

$$\frac{W_{IRR,i}}{D_{IRR,i}} \leq L_{R,i} . \quad (9)$$

Below is presented the discussion of the water abundance-based constraints.

While the assumption of the sectorial production structure's scalability implies the unchanged regional water productivity coefficients, in fact productivity is likely to decline as an effect of the «conservative» investment strategy in the highly productive regions, due to diminishing returns. Meanwhile, the reduction of the output in the less productive regions might or

might not be associated with productivity growth, due to abandonment of the economy of scale, as evident from the data summarized above. This allows identifying the national production output value in the model as an optimistic, i.e. upper bound, estimation of the productive potential in the economy under the water use restrictions imposed.

The land and water productivity and land irrigation demand coefficients were calculated based on the region-level data on industrial and agricultural output, as well as agricultural land stock from the State Statistics Service of Ukraine (2013, 2019b), the data on water abundance and water use volumes by categories from the Ministry of Environment and Natural Resources (Melnychuk et al., 2012; State Statistics Service of Ukraine, 2019a). Two model solutions were obtained, based on the average 2007-2011 and 2018 data sets. As the regional water abundance data has not been updated during the study period, the differences between the modelling results of the data set can be fully attributed to water productivity-related factors in the economy.

The water use restrictions for the model were based on the regional water balance data, available from the Ministry of Environment and Natural Resources. We have used the national water footprint concept and the generalized water ecosystem protection scenarios (Richter et al., 2011; Gleeson and Richter, 2017) to establish the water use restrictions at 10% of the local water abundance at the regional and the national level, both for surface water and groundwater. The concept of grey water (Bonamente et al., 2017) has been applied to establish the waste water volume restrictions to 80% of the local water abundance. Due to application of local, rather than the total abundance, and the coefficients corresponding to the estimated high level of ecosystems protection, the resulting restrictions constitute the strongly sustainable water use volumes. The sustainable grey water scenario would include the assigned volume restrictions as well; however, environmental control of waste water compositions would be required to maintain safety, which might require occasionally exceeding the identified restrictions to achieve safe pollutant concentrations. These features of the scenarios associated with the numerical restrictions in our model allow identification of the final results as plausible estimations of sustainable output potential of the national economy as a whole. Finally, the land use restrictions assume a conservative scenario, with the highest allowable agricultural areas for the regions assigned at the current figures in the respective data sets.

The complete solution of the optimizing model, obtained using the MS Excel solver, includes the national and regional total, industrial and agricultural production output values, water use volumes and structure, and waste water volumes. Nevertheless, due to the nature of modelling assumptions, the regional distribution of production, unlike the modelled national figures, is not expected to present realistic estimations. On the other hand, the model allows further clarification of the relative regional productivity potential taking the economy-wide competition into account. For these reasons, without overestimating the relevance of the modelling estimations, we report the numerical results partially in Table 4. We further present the qualitative classification of the regions' output frontier estimations in their comparison to the actual baseline output data, identifying two groups, the regions overutilizing and underutilizing their sustainable production potential. All of these results are reported for both data sets used for solution.

Table 4 as well reports the production output potential estimates transformed into the GDP potential of the national economy, based on the approximate GDP shares of industrial and agricultural sector, and assuming the unchanged share of value added, which likely overstates the estimations slightly. The nominal sustainable GDP potential is not high enough to reach the per capita level of the more developed Central and Eastern Europe countries. Moreover, the estimation value is only 4.3% higher for the 2017 data set, which may suggest absence of sectorial and technological restructurization during the period in consideration, attributing the water use decrease and productivity improvements to cyclical factors mostly. The output increase coefficient equal to 0.89 for agriculture in the 2018 set is the alarming result, suggesting highly unsustainable water footprint of the sector, which has likely caused the generally lower sustainable GDP frontier value. This suggests that water limitations may be even more relevant for sustainable development prospects compared to the well known energy-related issues.

The identified regional classification remains largely unchanged for the two sets, as reported in Table 5, with the regions overutilizing their sustainable capacity are assigned the 0 value. Qualitatively, these regions face the major economic risks of insufficient water supply, but should not divert excessive resources towards hedging those risks. The capacity-underutilizing regions generally have risks of future inefficiencies, and turn out to be additionally groundwater-reliant. Four

regions, Chernivtsi, Chernihiv, Mykolaiv and Luhansk, have moved from the «underutilizing» to the «overutilizing» group based on the 2018 set, while water productivity improved for the first three. While the improvements in productivity ranking can be explained by the country-wide productivity changes, the differences between the rank-based and the model-based classification demonstrate the impact of taking the actual water abundance and spatial competition for water resources into account. These results differ from the previous studies which indicate no pronounced spatial differences in water efficiency at least in agricultural production across the Central and Eastern Ukrainian territories.

It is important to stress at this point that, while the modelling results most certainly call for sectorial restructurization and innovation on the regional level, no conclusions pertaining to any particular region, its output potential or water-related «competitiveness» can and should be made

Table 4:
Numeric estimations of the water-based sustainable production frontier in the economy of Ukraine

	2012	2018
Nation-wide output, mln UAH		
<i>Agriculture</i>		
At the current water use	285652.9	471216.1
At the frontier	640876.0	420707.9
<i>Industry</i>		
At the current water use	1372822.2	3045201.9
At the frontier	9158763.2	35328011.6
<i>Total</i>		
At the current water use	1658475.1	3516418.0
At the frontier	9799639.2	35748719.6
Output increase coefficient at the frontier		
Agriculture	2.24	0.89
Industry	6.67	11.60
Total	5.91	10.17
GDP structure (2015)		
Agriculture	13.3%	13.3%
Industry	24.4%	24.4%
GDP increase at the frontier	2.55	3.57
Nominal GDP, USD billion	176	131
Frontier GDP, USD billion	448.67	467.99

Source: Author's calculations based on data by State Statistics Service of Ukraine (2013, 2019b)

Table 5:
Classification of the regions of Ukraine based on utilization of their estimated sustainable production sustainability (0 for the regions overutilizing their capacity), 2012-2018

	2012	2018
Cherkasy	1	1
Chernihiv	1	0
Chernivtsi	1	0
Dnipropetrovsk	0	0
Donetsk	0	0
Ivano-Frankivsk	1	1
Kharkiv	1	1
Kherson	1	1
Khmelnytskyi	1	1
Kirovohrad	1	1
Kyiv	0	0
Luhansk	1	0
Lviv	1	1
Mykolayiv	1	0
Odesa	1	1
Poltava	1	1
Rivne	0	0
Sumy	1	1
Ternopil	1	1
Transcarpathia	1	1
Vinnitsya	1	1
Volyn	1	1
Zaporizhzhya	0	0
Zhytomyr	1	1
Kyiv City	1	1
Crimea AR	0	n.d.
Sevastopol City	0	n.d.

Source: Author's own calculations

based on the presented model, which is essentially nation-level. Nevertheless, the model confirms the possibility of different, and hardly predictable based on the macro-level indicators alone, regional risk profiles related to water abundance, sustainability, water resource competition and administration conflicts, as well as to the regional investment strategies. These risks should be mitigated at the level of the national water policy and management strategy, which defines the governance implications of our results.

4.3. Implications for sustainable water management strategy

The modelling exercise reported above allows making two major intermediary conclusions. First, despite the improvements in the industrial water productivities across regions, as well as nationally, the model suggests the existence of negative trends in the national water use efficiency, particularly within the agricultural sector, which hinder the prospects of sustainable development drastically. This has been estimated quantitatively and demands further structural reforms and innovations. Second, the existing interregional water productivity gaps were, by including additional factors into the model, refined into two sustainability risk profiles, characteristic for regions on the basis of their sectorial structure, but as well of their hydrogeographical position, water abundance and relative contribution to the national economy. While the exact classification of the regions between the two groups may be contingent upon local factors not captured within the model, which makes it unsuitable for any region-level conclusions, it is crucial at this point to emphasize that the diversity of the risks and conflict sources requires a degree of adaptivity and flexibility of water governance frameworks in place. Both groups are prone to conflicts of various origins, which would involve the level of the national government in one way or another.

The regions of the first group face the risks of insufficient water supply mostly due to climate change-related increase in fluctuations of water balance. Due to the slower dynamics of water productivity, which is in turn caused by high share of accumulated industrial capital, the water supply risks are directly transmitted to productivity risks, on the background of high capital expenditure requirements of industries. The efforts to mitigate these latter risks and cover capital expenditures may include production price increases, additional environmental pressure, and intense direct investment market operations, all possibly accompanied by political pressure to gain access to additional national and/or regional level budgetary support, particularly by means of regional and territorial development programs. All of the mitigation instruments mentioned involve the political dimension, as they may bring up issues of utilities' affordability, environmental policy and sectorial priorities of national economic development. Some of the potential conflicts in these areas may be located on subnational levels, which is possible for the conflicts over environmental issues, but some may further contribute to interregional tension as well as the ongoing politicization of energy and sectorial issues at the level of the national governance.

The regions of the second group, unlike the previously mentioned, are exposed to risks related to baseline water supply in addition to the supply fluctuations exacerbated by climate change. While the lower water supply is associated with reduced fixed capital formation rather than reduced depreciation coverage, the available risk mitigation instruments only include diversification of water sources by shifting towards groundwater, which is visible in the empirical data analyzed. While the related conflicts may be limited by narrower territorial scope due to smaller production scales, their intensity may be much more severe on the level of territorial communities. Besides, the baseline water supply scenario includes risks of future water inefficiencies due to development of water-extensive industries through non-differentiated attraction of resource-oriented investments to regions and communities. The major difference from the first group is constituted by the potentially conflict-prone attempts to achieve mitigation of the latter risks, which is desirable for territorial sustainability transition. The differentiated support of local investment projects, as well as competition between businesses for growth-oriented budgetary support requires strong institutional frameworks to prevent corruption as well as politicization of regional development, which can result in the rather unnecessary involvement of the national government in the conflicts.

The above considerations are presented with the major aim to emphasize the high degree of uncertainty in water abundance impact assessment. The dimensions of the uncertainty include the possible climate change-related scenarios, the dynamics of water use and investment development, which shape the long-term sustainability prospects, as well as the uncertainty in the modelling forecasts. This requires a high degree of adaptivity but, on the other hand, uniformity, from the multi-stakeholder water policy institutions on all levels of national economic governance.

The possibility of achievement of both adaptivity and uniformity of conflict prevention and resolution mechanisms within the strategy is the major criterion to assess the existing institutions and projects in the ongoing water policy reform.

The recent parliamentary hearings recommendations on environmental policy priorities to the year 2025 state the completeness of legislative implementation of the EU Water Framework Directive (Cabinet of Ministers, 2017), while noting the lack of nation-level programs targeted towards the specific environmental issues in the water sphere, such as revitalization of Dnipro (Verkhovna Rada of Ukraine, 2020). At the same time, the Water Policy Strategy Green Book emphasizes the development and implementation of the River Basin Management Plans, as required by the Directive, as the key location of strategic issues. The legislative, rather than merely regulatory, embodiment of the required multi-level and multi-stakeholder participation could contribute to the required uniformity of participatory planning and control across regions and communities, which is not presently fleshed out in the approved procedure of the Basin Management Plans development.

The Green Book includes fundamental guidelines which can be considered favourable for the required institutional structure. These include the increased role of water rent and environmental taxation, presently low and inefficient, at some expense of the administrative regulation currently in place; efficient delimitation of groundwater basins to complete the coverage of regional and territorial water use frameworks; the potential of Basin Management Plans to induce water efficiency requirements for the existing productions and best available technology requirements for new productions; the two-level governance and participation structure, consisting of basin councils and the National political water dialogue. The recent policy recommendations and facilitation experience accounts from the literature that could be additionally taken into account to further develop the institutional framework include the following:

- 1) the necessity of public-private clustering in the sphere of water use for conflict prevention and resolution at the lower levels (Romaschchenko et al., 2015);
- 2) further implementation of River Basin Management requirements into the Water Code (Yara et al., 2018);
- 3) the framework for participatory water scenario development with practical cross-fertilization and the framework for incorporation of scientific knowledge (Zhovtonog et al., 2011).

More generally, an institutional blueprint for conflict management under the noted sustainability-motivated limitations and uncertainties in water use is present in Ukraine. Nevertheless, it additionally requires, for comprehensiveness and efficient implementation, first, the legislative participatory framework for cooperation and communication between territorial communities, basin councils and the National political water dialogue, and, second, strengthening of the link between the River Basin Management plans and regulation of water extraction, in addition to technology requirements, by economic and administrative measures.

5. Conclusions

This paper aimed to contribute to water policy discussion in Ukraine by bringing up the issues related to water efficiency and abundance risks beyond the immediate context of environmental policy, but rather as prerequisites for sustainable economic development. The dynamics of average water productivity and water use in the economy are as such inconclusive on development prospects, as are the economic estimations of natural resources productive potential not taking the sustainability-motivated limitations of resource use into account. This has motivated application of the production possibility frontier model of regional water use structure which, despite its limitations, has allowed direct interpretation of sustainable national water footprint concept, and the relevant quantitative norms, in terms of the GDP potential. The estimations of the latter indicate high relevance of water use for sustainable development prospects, comparable to or even higher than the impact of well known issues related to energy. Unlike the previous studies identifying little spatial difference in sectorial water efficiency across the Ukrainian territories, our results show two possible risk profiles for regions, characteristic by different origins and scopes of conflicts, as well as channels of involving the national government level.

In their policy implications, our results call both for stronger uniformity and higher adaptivity of the water policy and management frameworks. Unlike stated in the recent parliamentary hearings recommendations, the legislative basis of water policy requires further development to incorporate the participatory framework for cooperation and communication between territorial

communities, basin councils and the national water policy forum, as well as to strengthen the link between the River Basin Management Plans and enforcement of water use and efficiency requirements.

The previous studies and pilot project results should be further taken into account and integrated in order to develop a strong multi-level institutional framework for participatory water management, which constitutes the first major direction for future research. Furthermore, the comparative assessment of administrative and economic instruments should be performed within the context of river basin management to choose the policy mix for regulation of both new and existing water users. Finally, the processes, factors and stimuli for public-private clustering in water use should be studied further to inform the measures of conflict prevention and resolution at the lower governance levels, which is the relevant issue for majority of the Ukrainian regions, which presently face the strategic task of preventing future water inefficiencies while preserving transparency and inclusivity of their investment policy.

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