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Development of a prototype composite index for resilience and security of water-energy-food (WEF) systems in industrialised nations

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ABSTRACT

The Water-Energy-Food (WEF) nexus is a dynamic and complex system, in which the resources of water, energy, and food are inextricably linked. The system faces a number of threats including man-made hazards, e.g. overpopulation, urbanisation, ageing population, terrorism and geopolitical upheaval, and natural hazards such as climate change and extreme weather events. General indicators for the WEF nexus provide information on current access and availability of water, energy and food to a population. However, in industrialised nations such as the UK, such information is often masked by the consistently high access and availability of WEF resources. This paper proposes a composite WEF resilience index formed by aggregating two sets of indicators: one representing the availability level of WEF resources in terms of three WEF sectors; and the other representing population access to the resources at the household level. The WEF availability and the household accessibility indicators were calculated separately within the water, energy, food, and household sectors. Within each sector, an Analytical Hierarchical Process (AHP) was used for weighting sub-indicators based on experts' evaluation of the relative importance among the sub-indicators. This allowed us to synthesize individual opinions using expertise level in a group decision-making framework. A pilot study was performed on the UK WEF nexus to measure resilience in recent times. This prototype composite index can be used for exploring the resilience of the WEF systems to shocks and changes in the presence of high WEF access and availability.

1. Introduction

Water, energy and food are critical resources that are inherently interlinked (Scott, 2019). For example, water is used in the production of food and energy; energy is used to pump, treat and distribute water and it is also used in the manufacture, harvesting, storage, transportation and cooking of food; crops and food waste are increasingly being utilised as an energy source (Hoolohan et al., 2018). Ensuring a secure and resilient supply of these resources to all human beings is a challenge that spans scales, from local to global (McGrane, 2019). A secure and resilient WEF system can be conceived as one in which everyone has access to sufficient clean water, energy and nutritious food at all times (Ingram, 2011). This is a particular challenge because of the interlinked nature of WEF resources and because the system faces a number of potential threats such as climate change, population growth and urbanisation, poverty and terrorism. General indices for the WEF nexus and for the individual components, for example, the Global Food Security Index (Santeramo, 2015), often aim to be applicable across all nations allowing intercountry comparison. These indices highlight current access and availability of water, energy and food to the populace, issues that are clearly more important to less industrialised nations. However, in industrialised nations these indices are not as informative as in less industrialised nations, given the consistently high access and availability of WEF resources. This calls for a new index, or a composite indicator, which can be used to explore the resilience of such systems to shocks and changes without being masked by the currently high access and availability. An index that can be applied to regions at a sub-national scale would also allow variability within a country to be identified. With the focus on industrialised nations such as UK, we develop a prototype composite index as a resilience measure for the

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Water-Energy-Food (WEF) nexus. This work was carried out as part of the WEFWEBs project, which examined the data and evidence for the water, energy and food systems and their interactions and dependencies within the local, regional and national environment (Scott, 2018).

Composite indicators are useful tools that have been widely applied across a spectrum of academic disciplines to represent a diverse array of data (Becker, 2017). Given the existence of a large number of indicators in the WEF nexus, it is particularly useful to develop a resilience measure via a composite index approach. Development of composite indicators is a common approach for a quantitative assessment of the WEF nexus (Albrecht et al., 2018) particularly because they are useful tools for working across transdisciplinary boundaries (Endo et al., 2015). Existing indicators for individual components of the nexus are abundant, e.g. Global Food Security Index (Rosegrant et al., 2003), Water Exploitation Index (Marcuello, 2012), Energy Supply or Demand Index (Kruyt, 2009). Typically, such indicators include the constraints imposed by availability of the other two WEF resources, but do not explicitly consider the feedback effects on those resources which are essential. Of the indicators that cover the WEF nexus as a whole, many have been developed for a specific scale or context, for example river catchments (de Strasser et al., 2016) or irrigated agriculture (Martin-Gorriz et al., 2014). Other composite indicators have been developed for the WEF nexus, considering the inter-sectoral linkages, at the national scale to enable global inter-country comparisons and rankings, e.g. the Pardee Rand Food Energy Water Index (Willis et al., 2016), or at different geographical areas for the assessment of resources (Giupponi, 2017). These indicators emphasis on resource availability, without considering much about the accessibility of the population to the resources. One indicator developed recently focused on the Mediterranean climate zone (Saladini et al., 2018). This allowed a focus on issues that are particularly relevant in this region, such as the production of cereal crops and the specific characteristics of the population. This kind of zoning by climatic area is a common way of grouping regions with similar features with respect to natural resources, particularly relating to water resources and agriculture. For similar reasons, but reflecting socio-economic dimensions of the WEF nexus, Ozturk (2015) focused on countries with emerging economies. Again, this allowed a focus on the key priorities in this context. More recent work addressed similar issue with a focus on developing countries (Nhamo, 2020a,b).

Following the same reasoning, the aim of developing a composite indicator in WEFWEBS is to explore the resilience and security of the Water-Energy-Food (WEF) nexus in industrialised countries which are fairly secure. The resilience aspect of the index allows us to measure the robustness of the system to potential threats. Resilience in this context is a composite notion of adaptability, recovery, resistance or restructuring of the system following a disturbance or perturbation (Walker et al., 2004). This indicator can go beyond simple measures of accessibility and availability of resources, while considering interconnections across the system. The aims of this work were (i) to develop a composite indicator for WEF resilience and security and (ii) to illustrate the use of this composite indicator with a case study in UK using available data from 1990, 2000, and 2010 and to identify the challenges in operationalising such a composite indicator.

Section 1 has described the motivation of developing a composite indicator for measuring the resilience of the WEF system in an industrialised country. Section 2 describes the methodology used including the selection of component indicators, the collection of data, the design of an online questionnaire, and a weighting procedure using Analytical Hierarchal Process (AHP) (Saaty, 1980), to derive appropriate weights for the component indicators. Section 3 presents the results of the weighting procedure and examines a case study to explore the resilience in UK across years. Section 4 closes this paper with a discussion.

2. Methods

The approach to develop this new index followed a widely used procedure (Joint Research Centre-European Commission, 2008), including identification of indicators that characterised the water, energy and food resources and the population access to these resources. In the first step, we designed a questionnaire to survey a group of experts, asking them to rank the importance of the indicators following a structured process. The ranks were then used to produce a weighting for each indicator culminating in the weighted composite WEF index. The second step was to derive the weights for every single indicator within in each sector. In order to generate the set of weights combining individuals' judgements, an analytic hierarchy process (AHP) process that combining individuals' judgements based on their level of expertise was applied. The third step consisted of data collection and standardization for indicators identified within the water, energy, food, and household sectors. Computation within sectors and aggregation across sectors were completed in the last two steps.

A flow chart of above steps is given in Fig. 1, with further details given in Fig. 2.

2.1. Survey approach and development

Our approach was for the project team to identify an initial range of indicators and for survey participants to then consider these (via exhaustive pairwise comparison) in order to identify which they considered most important. The initial set of indicators was identified using a number of existing indicators as a basis (e.g. global food security index, the Pardee Rand Food Energy Water Index). A preliminary survey highlighted that it was difficult for participants to make pairwise comparisons between indicators that were relevant at very different scales; e.g. comparisons were difficult between indicators for the large-scale availability of WEF resources and their accessibility to individuals and households. For this reason, a revised structure for the composite WEF indicator was developed (Fig. 2). This included an additional composite sub-indicator which was used to group indicators relating to the accessibility of WEF resources to the household, whilst indicators relating to the availability of each resource at larger scale were grouped separately. The accessibility of the population to each of the resources could have been represented using three sub-indices rather than one. However, this would have led to replication of the income inequality indicator across the sub-indices because of the important role of household finances in access to WEF resources. As such, we decided to group these indicators together. This structure limited the pairwise comparisons participants were asked to make on those that preliminary participants found most meaningful.

The survey participants were researchers in the WEFWEBs project, and two other related projects, namely WEFWEBs, STEPPING UP, and Vaccinate the Nexus. This participant group therefore included experts from water, energy and food sectors all of whom had exposure to the WEF concept. The group also included a range of scientists, economists and social scientists. All of the members of these groups were invited to participant in the online survey. In the online survey the rationale and process were described and a glossary of the indicators was provided (Appendix A; Table A.1). A list of these indicators is given in Table 1. Participants were asked to make pairwise comparisons between all of the indicators in each group. For each pairwise comparison, participants were asked to identify which of the two indicators they thought was more important for quantifying the resilience and security of WEF systems, and how much more important. The participants are specialists and have expertises relating to at least one of the WEF resources. The levels of expertise in each sector were used to derive the priority level of individual opinions, for example, higher priorities were given to individuals who claimed to be experts. In this way, individuals' judgement of the relative importance of indicators within each sector can be used to define a consensus in the group of participants.

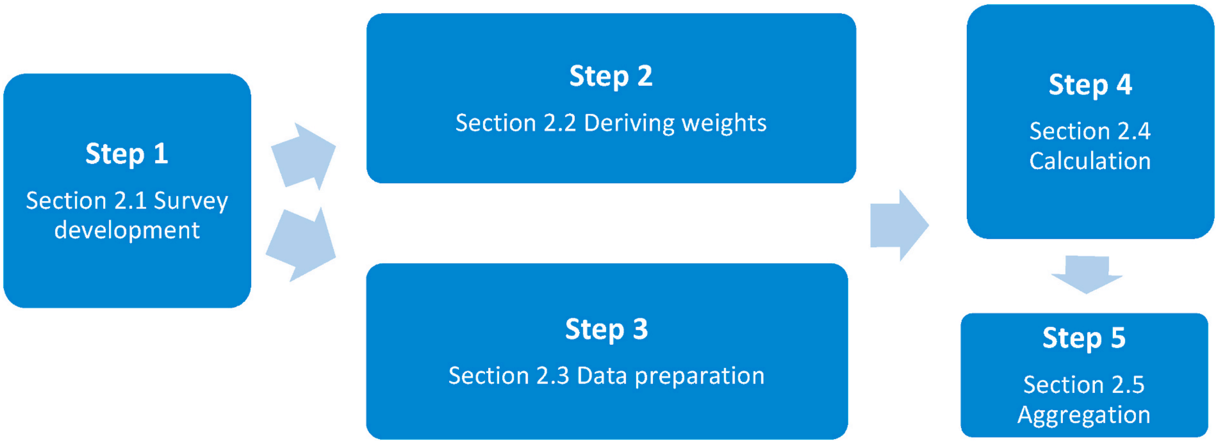

Fig. 1. Process chart.

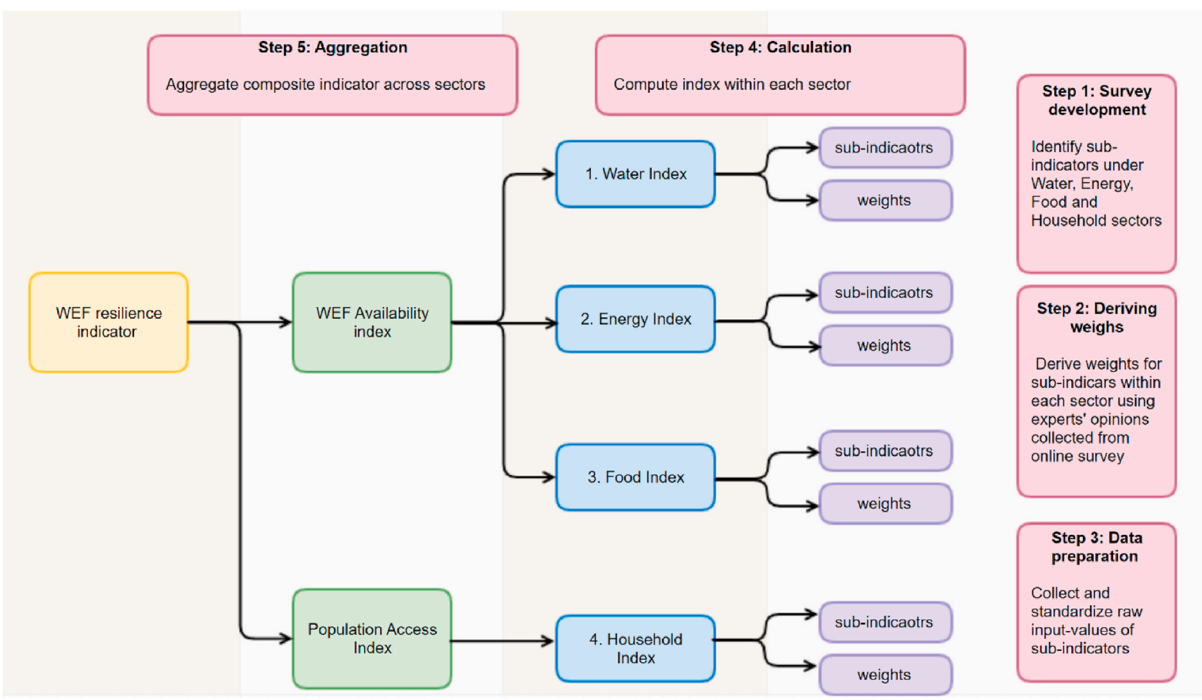

Fig. 2. Full Process chart showing the development of the composite indicator.

2.2. *Deriving weights – an analytic hierarchy process*

The AHP is an effective tool for complex decision-making (Saaty 1980) and has a variety of applications (Vaidya et al., 2006). In the construction of a WEF composite indicator, the AHP method is used to determine strength of relationship between general indicators or sub-indicators through pairwise comparisons. It relies on judgements of experts to derive relative priority scales for sub-indicators within each sector. Assessment of pair-wise sub-indicators results in a large comparison matrix from which the weights of selected sub-indicators can be evaluated based on an individual's level of expertise. Hence the weighting for each sub-indicator was determined via expert opinions through the online survey responses, and the AHP method was used to compile multiple responses and synthesize experts' opinions in deriving the weights. The AHP approach generate two matrices A and B, which store the information of participants' self-graded expertise levels and the importance scales of sub-indicators given by participants in the pair-wise comparison exercise, for deriving the weight w of sub-indicators within the four sectors. Descriptions of the matrices and their content are given in the following sections.

2.2.1. *Matrix A*

In each of the water, food, energy, and household sector, we implement AHP to compute the weights for the different indicators. We start by creating a pairwise comparison matrix A. The matrix A is a $m \times m$ real matrix, where m is the number of individuals participating in the survey. a_{jk} takes the values in Table 2. Each entry a_{jk} represents the expertise level of the j^{th} participant relative to the k^{th} participant. If $a_{jk} > 1$, the j^{th} participant has more knowledge or experience than the k^{th} participant, while if $a_{jk} < 1$, the j^{th} participant has less knowledge or experience than the k^{th} participant. If the two participants have the same amount of knowledge or experience, then the entry a_{jk} is 1. The entries a_{jk} and a_{kj}satisfy the following constraint: $a_{jk} \times a_{kj} = 1$.

Once the matrix A is built, we derive from A the normalised pairwise comparison matrix A_norm by row and column normalization, equalling the sum of the entries on each column to 1, and then computing an

Table 1
List of sub-indicators with in four sectors.

Water availability	Energy availability	Food availability	Household accessibility
Water exploitation index	Diversity of energy supply	Food import capacity	Household income inequality
Water quality	Import dependence	Food safety	Average food affordability
Trend in water use	Energy intensity	Food waste	Energy affordability
Drought risk	Costs for economy	Volatility of agricultural production	Transport-related energy affordability
Exposure to climate change	Storage capacity	Agricultural infrastructure	Household energy efficiency
Average supply interruption time	Water foot print of energy	Resource demand	Water affordability
Energy use in water system	Food footprint of energy Trend in final energy demand	Food price volatility	Household water efficiency Food waste

Table 2
AHP Scale of expertise level (a_{jk} values) Each entry a_{jk} represents the expertise level of the j^{th} participant relative to the k^{th} participant.

AHP Scale of expertise level in pairs	Numeric Rating
Much more knowledge	3
More knowledge	2
Equal knowledge	1
Less knowledge	1/2
Much less knowledge	1/3

m-dimensional column vector v by averaging over each row of A_norm.

2.2.2. Matrix B

The matrix of importance is a $n \times m$ real matrix S. Each entry s_{ij} of S represents the score of the i^{th} the indicator with respect to the j^{th} indicator. In order to derive such scores, a pairwise comparison matrix $B^{(j)}$ is built for each of the m participants, $j = 1, \ldots, m$based on the participants' answers to the survey questions. Each entry $b_{ih}^{(j)}$of the matrix $B^{(j)}$ represents the relative importance of the i^{th} indicator compared to the h^{th} indicator under the j^{th} participant's opinion. If $b_{ih}^{(j)} > 1$, then the i^{th} indicator is more important than the h^{th} indicator, while if $b_{ih}^{(j)} < 1$, then the i^{th} indicator is less important than the h^{th} indicator. $b_{ih}^{(j)} = 1$ if the two indicators are evaluated as having the same level of importance. Scales of $b_{ih}^{(j)}$are given in Table 3. The entries $b_{ih}^{(j)}$ and $b_{hi}^{(j)}$ are constraint by $b_{ih}^{(j)} \times b_{ih}^{(j)} = 1$, and $b_{ii}^{(j)} = 1$ for all i.

Table 3
AHP Scale of Importance ($b_{ih}^{(j)}$ values) Each entry $b_{ih}^{(j)}$ of the matrix $B^{(j)}$ represents the relative importance of the i^{th} indicator compared to the h^{th} indicator under the j^{th} participant's opinion.

AHP Scale of Importance for comparison pair	Numeric Rating
Extremely more important	9
Very strongly more important	7
Strongly more important	5
Moderately more important	3
Equally important	1
Moderately less important	1/3 (0.333)
Strongly less important	1/5 (0.200)
Very strongly less important	1/7 (0.143)
Extremely less important	1/9 (0.111)

2.2.3. Weights w

Then we apply to each matrix in $B^{(j)}$ the same two-step procedure as described for the matrix A, i.e. normalizing by column and averaging by row, thus obtaining the score vectors $s^{(j)}$, where $j = 1, \ldots, m$. The vector $s^{(j)}$ contains the importance scores of the evaluated indicator under the j^{th} participant's opinion. The score matrix S becomes $S = [s^{(1)}, \ldots, s^{(m)}]$, in which the j^{th} column of S corresponds to $s^{(j)}$. Once we obtain a vector v , from 2.2.1, and a score matrix S , we compute the weights as a vector by multiplying S and v, i.e. $w = S \times v$. Hence the i^{th} entry of w, w_i, represents the weight assigned by the AHP to the i^{th} indicator.

2.2.4. Expertise level for Matrix A

The values of expertise level were collected for the online survey, together with the individual's opinions regarding pairwise comparisons. The expertise level forms a criteria matrix which has a scale of 1–3, where 1 indicates no experience, 2 means some experience, and 3 represents much experience.

2.2.5. Importance scale for Matrix B

The relative importance was taken from the pairwise comparisons as indicated by individuals. The entries of the comparison matrices can be found in Table 3.

2.2.6. Consistency check

The last step in AHP is checking the consistency of the pairwise matrices, to make sure that the pairwise matrices, especially the importance matrices, are consistent. For example, if a participant answered the pair-wise comparison questions by saying indicator A is more important than indicator B, indicator B is more important than indicator C, but indicator A is less important than indicator C, then the answer provided by the participant is inconsistent.

Saaty (1987) proposed a measure of consistency, called the Consistency Index (CI), for a pair-wise comparison matrix, and compared it with a Random Consistency Index (RI), which is the CI calculated from a randomly generated pair-wise comparison matrix. CI is defined as $CI = \frac{\lambda_{\{max\}} - n}{n-1}$, since Saaty (1987) proved the largest eigen value $\lambda_{\{max\}}$ is equal to the size of comparison matrix n for any consistent matrix. Values of RI are given in Table 4.

The consistency check was done by computing a consistency ratio (CR), CR=CI/RI, and accepting a matrix as consistent if its CR is lower than a threshold value, typically 0.1 (Wedley 1993). More discussion about AHP judgemental scale and choice of threshold value can be found in (Goepel, 2019).

2.3. Data preparation – collection and standardization

As given in Appendix A, the data for the sub-indicators are gathered from various sources, and the raw data have very different scales and thus need to be standardized. We used the Min-Max approach that normalises indicators to have an identical range between 0 and 1 by subtracting the minimum value and dividing by the range of the indicator values (Joint Research Centre-European Commission, 2008). We adapted the Min-Max normalization technique for two situations. Equation (1) was used if a high value of an indicator is preferred for better resilience, or alternatively, Equation (2) is used in the opposite situation when an indicator is preferred to have a lower value.

Table 4
The mean consistency index of randomly generated matrices (Saaty, 1987).

n	1	2	3	4	5	6	7	
RI	0	0	0.52	0.89	1.12	1.26	1.36	
n	8	9	10	11	12	13	14	15
RI	1.41	1.46	1.49	1.52	1.54	1.56	1.58	1.59

$$x_i = \frac{X_i - Min(X_i)}{Max(X_i) - Min\ (X_i)} \tag{1}$$

$$x_i = \frac{Max(X_i) - X_i}{Max(X_i) - Min\ (X_i)} \tag{2}$$

X_i represents the actual value of the i^{th} indicator, and x_i denotes the normalised values of the i^{th} indicator.

2.4. Calculating the composite indicator – the weighted average

Under each sector, the compositor indicator was computed as a weighted average x_w ,

$$\overline{x}_w = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \tag{3}$$

Where x_i represents the standardized general indicators, which have an identical range [0, 1], and w_i denote their corresponding weights.

2.5. The overall indicator – aggregation across sectors

Let R denote the resilience metric during a certain time period. R is calculated as follow:

$$R = \sum q(pW + pE + pF) + (1 - q)H \tag{4}$$

$W, E, F,$ *and* H represent the weighted indicator x_w, as in Equation (3), computed individually following the AHP for the Water, Energy, Food and Household sectors using indicator data collected in different years to allow comparison of WEF resilience across time. After the computation of the four composite indicators under different sectors, we first combine the Water, Energy and Food indicators, by giving equal weights, $p = 1/3$, to obtain the WEF Availability indicator. The Household indicator, as explained in earlier section, is regarded as the Population Access indicator. Our WEF resilience indicator is then composed of both the WEF Availability indicator and the Population Access indicator (see Equation (4)). The weights q and $1 - q$ for both were determined by answers to the survey question "which of these are more important – the WEF Availability indicator or the Population Access indicator?" q denotes the proportion of individuals who answered with "the WEF Availability is more important".

3. Results

Following the process chart in Fig. 1, we present the results for the five steps in the following subsections.

3.1. Survey results

Out of the total 25 participants who completed the survey, 25 completed the questions in the water sector, 24 in the energy sector, 23 in the food sector, and 20 in the household sector. Table 5 presents their self-assessed expertise, with the most common assessment being some knowledge/experience.

Table 5
Survey statistics.

Sector	Total number of responses	a lot of knowledge or experience	some knowledge or experience	no knowledge or experience
Water	25	3	16	6
Energy	24	3	15	6
Food	23	7	10	6
Household	20	4	12	4

3.2. Indicator weights

We used the AHP methods to derive weights for general indicators within water, food, energy and household sectors, based on individual assessments (Matrix $B^{(j)}$ in section 2.2.5, for individual j), and then compiled multiple responses utilising the expertise levels (Matrix A in Section 2.2.4) to compute the geometric mean and determine eigenvalues as weights. Table 6 summarizes the steps for calculating weights for sub-indicators within each sector. Results are included in Appendix B.

3.2.1. Modification to the importance scale

Consistency checks showed that some individuals failed to provide highly consistent answers to the importance comparison questions in the survey. A solution to this problem is to collapse the original importance scale into a simpler structure. Table 7 gives the values of the new importance scale. We noticed that consistency improved if we aggregated the importance categories so that importance levels 3 and 5 were considered equivalent and levels 7 and 9 were also considered equivalent. Effectively, this meant that participants had chosen between three categories for importance rather than five. As a result, reducing the comparison levels greatly lowered the inconsistency in human judgements as shown in Fig. 3. Each bar represents the value of the consistency ratio computed from the comparison matrix constructed based on each participant's answers. The dashed horizontal lines are the chosen threshold value of 0.2, meaning matrices with consistency ratios lower than this value are accepted as consistent. Coloured bars in the figure are the consistency ratio of the comparison matrices computed from the original scale. Three different colours represent participants of different expertise levels. Gray bars corresponding to each participant are the CR computed using the rescaled matrices, and all of them are below the threshold value as indicated by the horizontal black dashed line. The value of 0.2 is slightly higher than the conventionally used critical value of 0.1 (Wedley 1993). This value was chosen deliberately because the comparison matrices contains a large number of pairs given the number of general indicators under each sector, a higher tolerance level of inconsistency would be appropriate.

By converting the importance scale, we obtained CR for individual comparisons matrices lower than the tolerant inconsistent level (0.2). This allows us to perform further AHP computation using the new importance scale.

3.2.2. Calculated weights within sectors

Results for weights within each sector are given in radar charts. Fig. 4

Table 6
Weight derivation.

1	m participants in total; j,k participants ID a_{jk} - the relative expertise level A - the comparison matrix	$A = \{a_{jk}\}, j,k \in 1, \dots, m$
2	n sub-indicators in total; i,h sub-indicators ID $b_{ih}^{(j)}$ - the relative importance; $j$participants ID $B^{(j)}$- the comparison matrix B - collection of m matrices	$B = \{B^{(j)}\} = \begin{matrix} B^{(1)} \\ \vdots \\ B^{(m)} \end{matrix} = \begin{matrix} \{b_{ih}^{(1)}\} \\ \vdots \\ \{b_{ih}^{(m)}\} \end{matrix} \quad i,h \in 1, \dots, n$
3	normalization and row averaging v – vector of length m $s^{(j)}$ – vector of length n S – matrix of size $n \times m$	$A \rightarrow v$ $B^{(j)} \rightarrow s^{(j)}$ $B \rightarrow S = \{s^{(j)}\}$
4	Compute weights for the n sub-indicators w – vector of length n	$S \times v = w$

Table 7
New scales.

Scale	Numeric Rating
Significantly more important	3 (7,9)
Moderately more important	2 (3,5)
Equal important	1 (1)

a) suggests within the water category that the drought risks and the water quality indicators seem to be two indicators that are slightly more important than the others. Fig. 4 b) highlights the diversity of supply among the energy indicators. Fig. 4 c) shows the importance of food indicators are very close to each other while food safety is of prime importance. Fig. 4 d) marked the income equality and average food affordability indicators as the most important sub-indicators in the household sector.

The red dots represent the weights calculated from the rescaled importance comparison matrices and the black dots are the weights derived from the original scale importance matrices. Slight differences can be observed in the values of weights by comparing the original and rescaled results.

3.3. *The weighting between WEF and household*

At the end of the survey, participants were asked to consider a pairwise comparison between the large-scale availability of the three WEF components, and the population access to these resources at a smaller scale. As before, the aim was for participants to consider the relative importance of each of these two factors in determining the resilience and security of the WEF nexus. The responses to this were highly varied across the whole range of possibilities. Interestingly, a Spearman rank correlation test indicated that there was a correlation between a participant's knowledge of food systems and the weighting they assigned to this comparison between WEF resource availability at large scale and availability to individuals at small scale ($\rho = 0.57$, $p = 0.009$). Participants with more knowledge of food systems tended to rate the household scale accessibility as more important, whilst those with less knowledge of food systems tended to rate the large-scale availability of WEF resources as more important. There was no significant correlation with expertise in other areas. This suggests that there are important differences in how experts from different areas view the importance of scale in the security and resilience of the WEF nexus. In computing the overall composite indicator, we take $q = 1/2$ (Equation (4)), assuming equal weights for WEF availability and Household accessibility.

3.4. *A case study*

In this section we apply the prototype index to the UK situation. We summarize the data availability in the water, food, energy and household sectors and compute the composite indicator in each sector for the years 1990, 2000, and 2010. Data for sub-indicators within each sector come from various UK and Europe government websites, including Eurostat, UK Parliament, OECD, NERC, and Scottish water, etc. We find that there are considerable challenges in accessing the required data which is in line with the findings of McGrane (2019). The water and food data are mainly available in 2010, whereas the energy and household data are available in 1990, 2000, and 2010. We apply Equation (1) and Equation (2) to datasets within each sector, standardizing sub-indicator values, and then use Equation (3) to calculate the weighted sum. All sectoral indicators and the composite index lie between 0 and 1 since we have used the standardized data (Appendix B records the standardized values of sub-indicators and their corresponding weights by sectors). Table 8 lists the sectoral indicators. All indicators are available in 2010, allowing us to compute the overall indicator using Equation (4). Using the time series of values, specifically for Energy and Household, we are able to evaluate how the resilience of certain sectors in the UK WEF system changed over time.

The composite indicator derived within sectors has a range from 0 to 1. We were only able to calculate the overall index for 2010 with a value

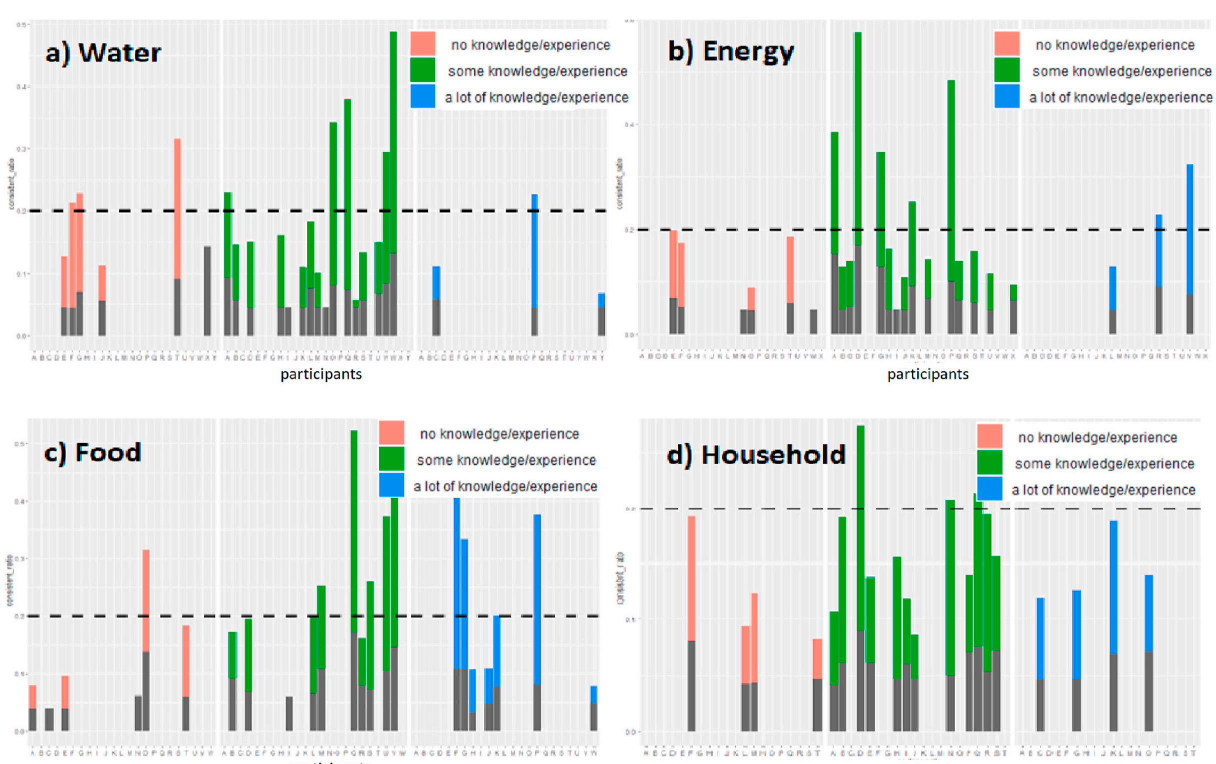

Fig. 3. Bar-plot of Consistency Ratio (CR) within four sectors. Colour bars are CRs grouped by expertise levels. Dashed lines represent the critical value chosen for the CR. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

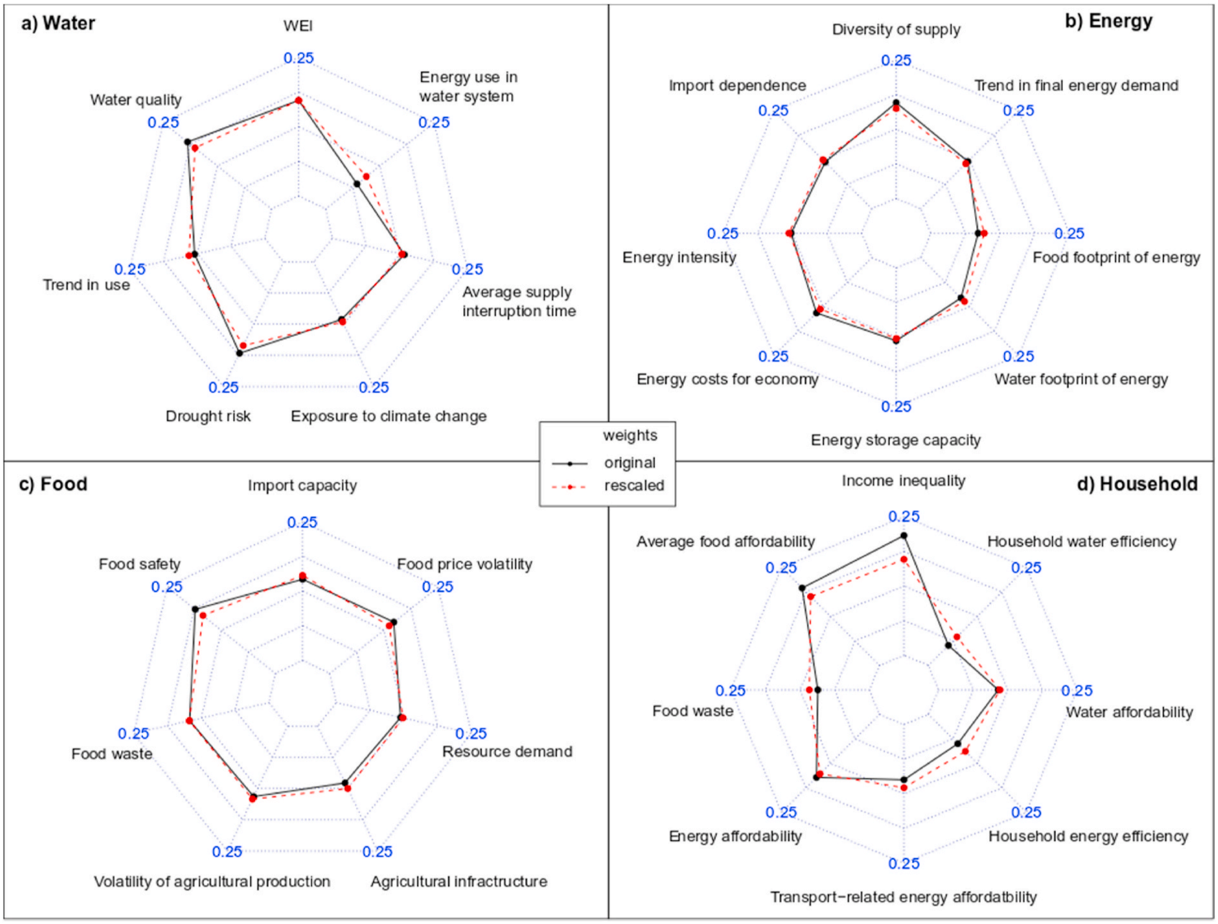

Fig. 4. Radar chart of weights for the sub-indicators in each sector as derived from expert opinion using the analytical hierarchy process.

Table 8
Indicator values in the UK.

Composite Indicators	Values (years) * for missing
Water	0.47 (2010) *
Energy	0.69 (2010) 0.52 (2000) 0.61 (1990)
Food	0.45 (2010) *
Household	0.31 (2010) 0.36 (2000) 0.29 (1990)
Overall	1.42 (2010) *

of 0.42 due to lack of available data and are therefore unable to comment on any trends. The resilience measure for the Energy sector however was obtained for 1990, 2000, and 2010, as the necessary data are all available at data. gov.uk in these years, and the values corresponding to these years are 0.61, 0.52, and 0.69. A higher value denotes higher resilience, the resilience indicators show that there was a decrease in 2000 and an increase again in 2010. The resilience measure for the Household sector was obtained for 1990, 2000, and 2010, from Office for National Statistics (https://www.ons.gov.uk/), and the values corresponding to these years are 0.29, 0.36 and 0.31. For the water and food sectors we are only able to calculate a value for 2010 at 0.47 and 0.45 respectively. It is clear from the calculations that the household sector shows lower resilience than the other 3 (large scale infrastructural) sectors.

4. Discussion

4.1. Reflection on the survey process

During the development of the survey it became clear that it was difficult for participants to make pairwise comparisons between indicators that were relevant at very different scales; e.g. comparisons were difficult between indicators for the large-scale availability of WEF resources and their accessibility to individuals and households. However, it is clear that for a WEF system to be resilient the resources must both exist and reach the users. This has been highlighted both in a number of composite indicators (Cottee, 2016; McGrane, 2019). To include indicators at both scales whilst avoiding difficult comparisons we introduced a basic structure for the index, with a single comparison between the different scales for which participants gave a weighting (Tables 3 and 7). It was interesting that the response of participants to this final weighting depended on their area of expertise, particularly knowledge of food systems. This perhaps reflects differences in the nature of food systems compared to water and energy systems as well as the current focus of research in these disciplines. Both water and energy are dependent on highly specialised infrastructure overseen by a few regulated bodies whilst food systems rely on a more distributed system and a complex network of actors. Additionally, food systems are global and it is acknowledged that there is sufficient food produced to meet global needs but it is the distribution and access to this food that is the challenge (Ericksen, 2008). Meanwhile water is typically managed at a local scale because of the expense of transporting it long distances in high volumes (Gleick, 2000). Energy is also typically managed predominantly at a local or national scale with some interconnections between countries (Hussey, 2012).

There is notably more variability in the weightings within the sub-indicator for the household compared to the other sub-indicators (Fig. 4). This perhaps reflects that the water, energy and food indicators drew heavily on a number of established indicators whilst there was less literature on the household scale within an industrialised context. It is also interesting that our analysis indicated the least resilience in the sub-index for the household scale compared to the resources at larger scale (Table 8). This highlights the importance of considering the household scale to improve the overall resilience and security of WEF systems.

4.2. Understanding the weighting process

The composite resilience index was compiled from general indicators in the water, energy, food, and household sectors. To derive such an indicator, a weighted average was taken from these indicators, and the weights associated with the indicators are determined by a group of individuals who are experts on at least one of the four sectors. The process of developing a resilience index in developed countries suggests different aspects are weighted differently in different context. The unbalanced radar plot suggests different consideration in different society; For example, household water efficiency is weighted less, as there is less social concern for this aspect because in UK water is not allowed to cut off for public health reasons.

A challenge for constructing such a composite index lies in i) identification of general indicators that are crucial to the overall resilience of water, energy and food systems in the UK and ii) development of an expert-weighting survey on significance of sub-indices and specific indicators. Difficulties arise not only in identifying suitable indicators, but also in acquiring data for the indicators (McGrane, 2019). General data availability at the appropriate scale is a huge challenge, the use of technology (e.g. sensors in households and buildings) offers one possible solution but is also a challenge given the potential intrusiveness of such technology. Our work highlights the need for consistent data collection across WEF sections and also the importance of including a measure at the household scale.

4.3. Future work on adding linkages to metric

One of the challenges in managing WEF resources arises because actions to reduce one indicator may have unintended consequences for other indicators. In this study, indicators that highlighted the use of the other resources (i.e. energy use in water system, water footprint of energy, food footprint of energy, resource demand for food) typically received lower weightings than other indicators. This suggests that, even experts directly involved in WEF projects, do not consider the interactions between the resources as the primary concerns for the resilience and security of the WEF system. However, it is not clear why this is and whether it is justified as it may be that the lack of previous shocks of this nature have created a false sense of security.

Currently, the indicator framework does not account for interactions among WEF resources explicitly. One future extension to this indicator framework could be to develop a network map of the key interactions between indicators and whether interactions are likely to be positive or negative. For example, an increase in the water footprint of energy would increase the water exploitation index. Mapping out these linkages could help when considering the likely effect of different actions to improve WEF resilience and security, as all of the indicators that were likely to be affected could be considered.

4.4. Limitations of the study

The WEF indicator was constructed in the AHP group decision-making framework, by first weighting sub-indicators based on experts' evaluation of the relative importance among the sub-indicators and then aggregating the derived weights and the measure of sub-indicators. There are a number of concerns in both the weighting and the aggregating processes. i) The small number of experts in each of the different fields can affect the importance weighting process if the sample of experts is biased. For example, in the household sector, the distribution of low, median, high expertise levels is about 20, 60, 20 percent. Other sectors have similar distribution. Nonetheless, a large sample of experts would bring increased robustness in the weight estimation process ii) Problems in the aggregation process comes from the challenges with defining and quantifying resilience, including not simply quantity and capacity. We have taken a simple definition of resilience to help narrow the potential sets of sub-indicators. Iii) Due to the lack of temporal data, it is difficult to compute the composite indicator over a long-time span for year-to-year comparison and iv) the problems of scale (geographical and process) make the combination of household with finer regional scale indicators again more difficult to achieve.

Given the data limitation, we were not able to validate the derived index or perform an uncertainly analysis. It is worth mentioning, however, one advantage of using AHP methods is that by resolving inconsistencies (Section 2.2.3) we managed to reduce uncertainties in the weighting scheme (Saisana, 2005). One possible extension of the study is by considering further techniques, such as the Delphi method (Linstone, 1975) which uses a forecasting process framework based on the results of multiple rounds of questionnaires, to improve this iterative survey process, when seeking wider opinions is not possible in a chosen panel of experts. This may help modify some of the items in our survey and produce an enhanced composite indicator for quantifying WEF resilience.

5. Conclusions

While we have used a well-recognised approach in the development of a WEF nexus resilience composite index, we faced a number of challenges in implementing the indicator. The first challenge is of course the definition of resilience which in this case we have taken to be the adaptability, recovery, resistance or restructuring of a system following a disturbance or perturbation, based on Walker et al. (2004). The development process starting from the survey, threw up challenges in making the necessary comparisons between indicators at the very different scales. This resulted in development of basic structure for the index. Participants also found difficulties in weighting all the different components, especially at household level, reflecting different levels of expertise in the WEF system. Our experience of the process of developing a resilience index for developed countries suggests different aspects are weighted differently in different contexts, arguing perhaps for the need of a dynamic index.

Aside from the challenges in defining the component indicators and appropriate weightings, there is a very clear need for consistent data collection. Our work highlights the need for consistent data collection across WEF sections and also the importance of including data at the household scale.

Finally, the indicator framework does not explicitly take into account interactions among WEF resources. A network map of the key interactions between indicators and whether interactions are likely to be positive or negative would be essential to develop.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2021.100124.

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