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地质环境健康适宜性评价指标体系与评价方法研究

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摘要: 人的健康与地质环境息息相关，地质环境对人群健康的影响一直以来备受环境、地质、医学等多学科领域研究者的关注。在环境健康影响评估方面，已有的研究注重从化学物质或工程建设等单一视角对健康风险进行评估，而从地球系统角度综合评估地质环境健康影响的研究尚不多见。本文提出从环境地球化学、区域地质背景、气候状况及人为活动强度等多维度出发，开展基于复合视角的地质环境健康适宜性评价指标体系与评价方法研究。本文建立了地质健康指数(GHI)评价方法，该方法按照 GHI 得分情况，将区域地质环境的健康适宜性分为优(85 分及以上)、良(75~85)、一般(60~75)、较差(50~60)和差五个等级，分别代表区域地质环境处于极适宜、适宜、较适宜、可能适宜与不适宜人群健康的状况。本文以浙江省安吉与龙游两县为例，对 GHI 法的应用进行了案例分析。GHI 法评价结果显示，两地在“气候状况”、“地质背景”与“人类活动强度”等三个分指数上得分相当，而在“环境地球化学”分指数上存在较大分异。这是因为安吉富硒土地农产品在富硒的同时重金属超标严重，而龙游富硒土地则无此类现象。两地 GHI 总指数得分显示，安吉地质环境的人群健康适宜性处于“良”级(78.16 分)，而龙游则处于“优”级(85.50 分)。调查发现，两地居民健康状况差异不大，居民平均预期寿命均优于全国平均水平，说明虽然安吉地质环境存在高 Cd、Ni 的地球化学特征，但富硒环境起到了一定弥补作用，使得安吉整体上仍处于“适宜”人群健康的水平。GHI 评价方法能够从总体上考虑与人群健康相关的地质环境要素，客观反映区域地质环境的健康适宜性状况，评价结果可以为合理利用有益健康的地质资源，以及规避不利健康的地质风险提供指导。

关键词: 地质环境；人群健康；适宜性评价；地质健康指数(GHI)；环境健康影响评估

要点:

(1)以地球系统科学理论为指导，开展了基于复合视角的地质环境健康适宜性评价指标体系与评价方法研究。

(2)建立了包含气候状况、地质背景、地球化学以及人类活动等要素的评价指标体系，使用层次分析法对各指标进行了权重赋值。

(3)以浙江省安吉与龙游两地为例，对 GHI 法的应用进行了案例分析。结果表明，GHI 法评价结果能够较客观地反映区域地质环境对人群健康的适宜性状况。

(4)地质背景相似的地区可以产生不同的健康响应，说明区域人群的健康特征是包括地质环境要素在内，及经济水平、饮食习惯等多因素综合作用的结果。

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人的健康与自然环境息息相关,区域人群健康特征是人与自然长期相互作用的体现。一定区域的岩石地层、地形地貌、气候条件以及土壤、水、作物等多介质的地球化学品质,造就了区域人群特定的生活方式和行为习惯,形成了独特的区域人群健康特征。事实上,早在 2500 年前,希波克拉底在他的著作《论空气、水和环境》中就强调了地质环境对人群健康的影响,中国自古也有“一方水土养一方人”的说法[1]。这些有关区域地质环境与区域健康和地方病等重要关系的古老研究,为今天医学地质与环境健康的研究提供了深厚的理论支持。

地质环境的人群健康适宜性是地质、环境、生物、医学等领域的重要研究问题,很多学者或机构从不同研究角度开发了不同的评价指标体系。其中,有关环境中不同介质污染物的人群健康风险评估最受各国学者关注。美国环境保护署(US EPA)[2-3]、欧盟(EC)[4] 等机构发布了一系列针对不同污染物的暴露风险评估指南、暴露参数手册等,建立了相对完善的评价体系[5-7]。中国国家卫生健康委员会也先后发布了环境中大气污染的人群健康风险评估技术规范(WS/T 666—2019)、化学物质环境健康风险评估指南(WS/T 777—2021)等文件,指导开展针对化学物质的健康风险评估工作。此外,中国十分重视大型工程项目的环境健康影响。在环境保护部门实行的环境影响评价制度中,将人群健康作为 10 大类建设项目的评价要素之一,要求新开政策、规划、工程、项目等对人群健康的影响进行评价[8]。

从现有研究成果来看,虽然化学物质健康风险评估体系完善,成果丰富,但都是基于单一视角的风险评价,主要考察大气、土壤、水等单一介质或某一类化学物质对人体健康造成的潜在影响。而建设项目的环境影响评估对人群健康的影响明显考虑不足,新的健康影响评估制度体系仍在建设之中[8]。在全球社会经济高速发展的今天,人群健康与地质环境的关系更为复杂,单一的环境与人群健康的评价方法已难以适应健康影响因素日益复杂化的局面。地质环境的人群健康适宜性研究,正在新的理论框架下快速开展[9-10]。本文提出从环境地球化学、区域地质背景、气候状况及人为活动强度等多维度出发,开展基于复合视角的地质环境健康适宜性评价指标体系与评价方法研究。研究成果有助于人们了解区域或局部地质环境对人群健康的适宜程度,帮助识别哪些地质要素对人群健康影响的权重更大。研究成果可以应用于健康地质评价、环境健康影响评估等工作,为更加可持续的社会、经济与环境发展提供支撑。

1　指标体系的构建与遴选

在地球漫长的演化过程中,地球表面逐渐形成了各地迥异独特的地貌特征、水系特征、生物特征和气候特征,塑造了千姿百态的自然景观,搭建了适宜人类生存发展的环境空间,实现了圈层之间的物质循环与能量传输[11]。地球物质与地质过程决定了人类生存环境的质量,直接或间接地影响着人群的健康。而自工业革命以来,人类活动的规模和强度不断增加,深刻改造着地表环境,亦反过来影响到人类自身的健康。呈现鲜明地域特征的“地方病”现象,就是地质背景、气候、水、土质量以及人为活动等多种复杂因素共同作用的结果[12-14]。自然地质环境条件叠加人为活动因素,构成了影响人群健康的地质环境要素系统(图 1)[15-17]。

从图 1 可见,对人群健康具有直接或间接影响的地质要素,包括气候状况、区域地质特征、地球物质的地球化学循环特征,以及广泛参与到地质过程中的人类活动等。对一定区域地质环境的健康影响进行评估,需要从这一复杂系统中提取科学合理的指标体系,构建稳健可靠的评价模型。

地质环境健康影响评价指标体系的选取主要遵循以下几个原则:①综合性。所选指标体系需要既能反映单一地质要素或局部特征,又能够综合反映地质环境系统特征。②科学性。需科学选取与人群健康密切相关的指标,各指标对健康的影响有据可依,能够客观反映一定区域地质环境对人群健康影响的差异。③简明性。地质环境系统结构庞大,功能复杂,与人群健康相关的指标数量繁多,应尽量选取代表性强、指标概念简洁明了的主要指标。④可操作性。各指标的数据获取途径方便可靠,计算方法简便,最好有现行的环境行业或卫生行业标准作为参照。

本文参考张文忠等[18-19] 提出的“宜居城市评价指标体系”、王秀峰等[20] 提出的“健康中国”评估框架,以及吴初国等[21] 提出的“国土资源可持续发展指标体系”,形成以气候条件、区域地质背景、地球化学质量和人类活动强度为主要维度的初级评价指标体系。经过对各项指标的重要性、敏感性和可操作性进行打分,对指标体系进行了筛选和调整,确定了共包含 15 个具体指标的地质环境健康适宜性评价指标体系(表 1)。

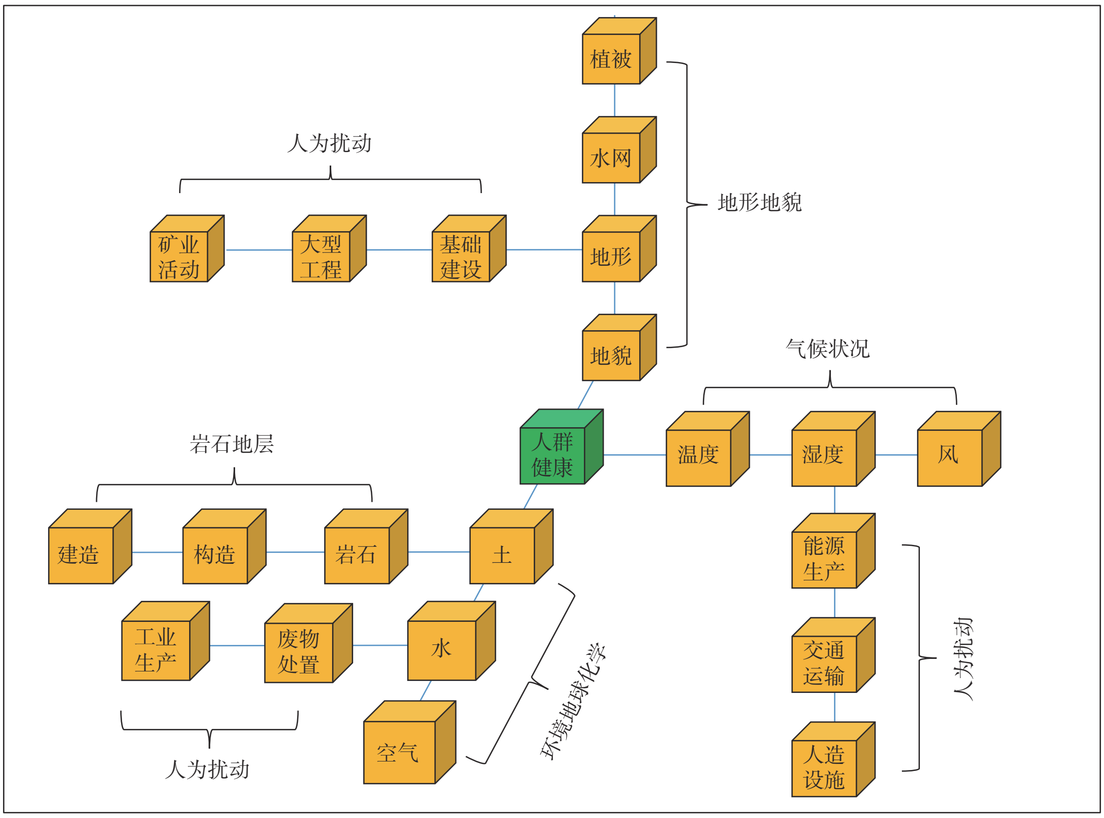

图1　影响人群健康的地质环境要素系统

Fig. 1　The conceptual linkage between human health and geological environmental factors. There're various geological environmental factors affecting human health in a composite way. Geological background characteristics, climate conditions, geochemistry behavior of elements and chemicals, as well as various human activities that have a profound impact on various geological processes, contribute jointly to an endemic public health status in a region.

表 1　地质环境健康适宜性评价指标体系组成与相应权重

Table 1　The evaluation indexes of geological suitability for human health and the corresponding weights.

总指数	分指数(权重)	指标(权重)
地质环境健康适宜性(GHI)	气候条件(0.32)	人体舒适度 (0.256)
		极端天气发生率(0.064)
	地质背景(0.16)	区域地壳稳定性(0.024)
		天然环境放射性(0.040)
		海拔高度(0.056)
		植被覆盖率(0.040)
	环境地球化学(0.36)	环境空气质量(0.108)
		灌溉水质量(0.043)
		饮用水质量(0.058)
		耕地土壤质量(0.043)
		农产品质量(0.050)
		人均水资源量(0.029)
		人均土地资源量(0.029)
	人类活动强度(0.16)	人口密度(0.080)
		人均工农业生产总值(0.080)

2　指标体系分析

2.1　气候要素指标

研究表明，气候条件对人群健康具有直接影响[22-23]。温度与呼吸系统疾病密切相关。据来自不同国家或地区的报道，呼吸系统疾病的日入院人次与日死亡数与日均气温存在“U”、“V”、“J”型等多种曲线关系[24-25]。人体通过对大气温度、湿度和风的直接感知，判断居住环境的舒适程度。该条件可以用人体舒适度(I_{BC})指标来表征[26]:

$$I_{BC}=(1.8\times T+32)-0.55\times\left(1-\frac{H}{100}\right)\times(1.8\times T-26)-3.2\times\sqrt{V} \qquad (1)$$

式中：I_{BC} 为人体舒适度指数，四舍五入取整；T 为日平均气温，单位为摄氏度(℃)；H 为日平均相对湿度，用百分数(%)表示；V 为日均风速，单位为米/秒(m/s)。

而当前更严峻的问题是，气候变化已影响到全球各个区域的天气状况。在 50 年时间尺度上，自 1970 年以来的全球变暖趋势比近 2000 年历史上的其他任何时期都要快，引发高温热浪、极端降水等极端事件发生的频率和强度增加[27]，导致热射病、心脑血管、呼吸道、神经系统疾病的发病率提高[28-29]。

综合以上考虑，本文使用人体舒适度以及代表

气候变化趋势的极端天气发生率两个指标来表征对人群健康产生影响的气候要素。

2.2 地质背景指标

地质背景主要描述岩石、地层、构造等地质体的特征、属性、空间分布与相互关系等[11],本文将这一概念扩展至地球表生系统的空间范围。这里共提取了和人群健康密切相关的区域地壳稳定性、天然环境放射性、海拔高度与植被覆盖率等 4 个指标,来表征构造、岩石、地层以及表生系统空间特征对人群健康的适宜性。

区域地壳的稳定程度是人类开展工程建设的基础,是人类健康发展的重要支撑[30]。岩石是土壤发育的母质,岩石的类型与性质决定了土壤类型和土壤所养育动植物的品质,进而影响区域人群的健康表现。在碳酸盐岩出露的区域,土壤中普遍含有较高的钙质,导致当地人群患尿结石病的风险明显升高[31]。在超基性岩的地质环境条件下,人们通过饮食、饮水等途径摄入 Fe、Cr、Ni 等毒害重金属元素的风险增加[32]。岩石类型与环境的天然放射性水平也有一定联系,环境中的总天然辐射剂量有大约 15% 被认为来自岩石和土壤中 U、Ra、Th 和 K 的 γ 辐射,60% 来自 Ra 的放射性衰变产物 Rn[33]。据报道,Rn 已成为继吸烟之后诱发肺癌的第二大因素[34]。

地貌因素促使人体所需微量元素发生不同尺度的聚集和迁移,从而影响人群健康[35]。在低谷、洼地、闭流等地表径流排泄不通畅地区,或地下水径流胶体滞缓地带,以及两种不同地貌单元的接合部位,当地居民易发氟中毒、克山病、大骨节病等地方性疾病[16]。在内陆高原、山地及丘陵地区,水土流失容易带走碘元素,造成地方性甲状腺肿病情严重[11]。海拔高度对人体心血管系统功能具有直接影响,随着海拔的增高,大气氧压力逐渐降低,导致受试人员的外周血管阻力明显升高,心脏收缩功能减弱[36-37]。通常认为超过 2000m 海拔人群患高山疾病的风险开始增加,并随着海拔的进一步增高(超过 3500m 以上),高山疾病变得更加普遍[38-39]。高海拔地区强烈的紫外线辐射还会导致皮肤癌和黑色素瘤的风险增加[40]。植被与绿地可以显著降低大气颗粒物的浓度,预防空气污染带来的健康风险[41-42]。Pugh 等[43] 应用大气化学预测模型发现,行道树可以降低 60% 的大气颗粒和交通扬尘。

2.3 环境地球化学指标

人体通过呼吸空气、饮水、摄入食物与地质环境间进行物质与能量交换,与环境保持着物质的动态平衡。早在 20 世纪 70 年代就有研究者发现人体血液中的元素含量不但与地壳岩石的化学元素丰度之间存在显著的相关性(r=0.75, p<0.05),还与海水中元素丰度之间存在更显著的相关性(r=0.84, p<0.01)[44],显示了生命与地表各圈层地球化学成分的重要联系。

20 世纪 60 年代起,日本和美国的研究者相继发现饮用水硬度与心血管疾病呈现明显的负相关关系[8]。同时期中国学者发现在中国东北到西南地区存在一条明显的“低硒带”(土壤 Se 含量小于 0.125mg/kg),与克山病、大骨节病的空间分布具有较高的一致性[45]。这两项里程碑式的研究带动了一系列有关地球化学环境与人群健康关系的研究工作,积累了丰富的研究资料[46-49]。人们普遍认为,地球化学元素与污染物以不同含量与形态存在于空气、土壤、水和食品中,并随时间与空间不同而不断发生变化。这些化学物质被人体通过饮食、饮水、呼吸、食土、皮肤接触等多种途径摄入,对人群健康产生有利或有害的影响。本文参考环境污染物人群暴露评估、化学物质健康风险评估技术与国土资源可持续发展指标体系,提取了环境空气质量、饮用水质量、灌溉水质量、耕地土壤质量、农产品质量以及水资源量和土地资源量 7 个指标,来表征对人群健康具有重要影响的环境地球化学要素。

2.4 人类活动强度指标

人类依赖于地表环境生存和发展,但人类活动又改变了自然环境,反过来影响到人类自身的健康和发展。采矿、耕作以及大型工程建设等人类活动使超基性岩石中的 Cd、Ni 等有害元素发生释放或移动,从而进入地表环境,参与到水和食物的循环中[50-51]。各种工业和农业活动还直接向水、土、大气中输入元素,重塑地表元素的空间分布格局。以元素硒为例,不但有煤和石油燃烧产生的含硒粉尘经大气传输和沉降在地表富集[52],更有施用硒肥、喷洒含硒农药、土地污泥处置等农业活动造成土壤硒含量直接增加[53-54]。工业革命以来,人类活动对气候变化的影响已不可逆转。由 IPCC 发布的第六次评估报告(AR6)对气候变化与人类活动的关系有了更加清晰的认识,将“全球地表温度”和“极端高温”事件的变化归因于人类活动的信度提升到“毋庸置疑”和“几乎确定”的水平[27]。

可以说,当前人类活动已影响和改变了全球及区域尺度自然物质的正常交换,给生物的生存和人类健康带来不容忽视的影响。究其根本原因,是人

口数量的不断增长致使资源和能量的需求不断攀升，密集的农业和工业活动给生态环境带来持续压力[55]。基于此，本文提取人口密度和人均工农业生产总值 2 个指标对人类活动强度进行表征。

3 评价方法与应用

3.1 评价方法

3.1.1 数据标准化与权重选择

由于现有资料缺乏可参照的对环境条件直接进行健康影响评价的标准，本文提出采用两步法对数据进行标准化处理，以完成地质环境健康适宜性的评价过程。首先，通过与各指标的全国平均水平、国家和行业标准规范等进行对照，确定所有指标对应的环境质量等级；其次，参照文献资料、世界和国家卫生标准等，对不同等级的地质环境质量可能对人群健康产生的影响进行评价，使用 0~100 分来衡量影响的程度。

需要指出的是，各指数和具体指标的权重选择是完成综合评价的关键。因此，完成了数据的标准化之后，需要对每项指标相对上一级的重要性进行判断，并给出相应的权重。本文的评价过程中使用层次分析法对各指标逐级进行相对重要性判断，得到各层次要素相对于上一层级要素的相对权重，以及各指标相对于系统整体的重要性权重。然后，对各指标的相对重要性进行判断，构建相对重要性矩阵，最终确定的各级指标权重值见表 1。

3.1.2 计算 GHI 指数得分

根据各具体指标权重和赋分计算各分指数得分（用符号 S 表示分值）。

$$S_i = \sum_{i=1}^{n} W_{ij} \times S_{ij} \qquad (2)$$

式中：i 代表第 i 个分指数；j 代表第 i 个分指数中第 j 个具体指标；W 表示权重值；n 表示每个分指数中的具体指标数。

最后根据各分指数权重和得分计算地质健康适宜性指数得分：Total S（GHI）。

$$\text{Total } S\text{（GHI）} = \sum_{i=1}^{4} W_i \times S_i \qquad (3)$$

式中：W_i 和 S_i 分别代表第 i 个分指数的权重值和得分。

3.1.3 评价结果表征

按照研究区的 GHI 得分来表征健康适宜性评价等级（表 2）。

在此基础上，调查当地对人群健康有益的地质资源情况，收集当地人口结构、预期寿命以及慢病、地方病、癌症等聚集性患病情况等信息，帮助对综合评价结果进行解释。

3.2 方法应用

使用地质健康综合指数法（GHI）对浙西地区安吉和龙游两地的地质环境健康适宜性进行评价，评价结果见表 3。从各项指数得分来看，两地的“气候状况”、“地质背景”和“人类活动强度”分指数的得分均相当，而“环境地球化学”分指数得分的差异较大。两地 GHI 总指数得分显示，安吉地质环境的人群健康适宜性处于“良”级（78.16 分），而龙游则处于“优”级（85.50 分）。

安吉与龙游两地均位于浙江省西部，地处长三角地理中心，属亚热带季风气候。虽然在全球气候变暖形势下，夏季易发高温热浪极端天气，但总体上气候温和湿润，舒适度高。两地广泛分布下寒武统荷塘组黑色岩系，以黑色硅质岩夹石煤层、磷矿层为主要岩性，地球化学以富 Cd、Ni、Se、Zn、As、S、Fe，低 Ca、Mg 为特征[56]。在安吉、龙游两地均发现大

表 2 地质环境健康适宜性评价等级

Table 2 GHI scores and the corresponding human health suitability levels.

级别	指数	描述
优	GHI≥85	极适宜
良	75 ≤GHI<85	适宜
一般	60≤GHI<75	较适宜
较差	50≤GHI<60	可能适宜
差	GHI<50	不适宜

表 3 GHI 法在浙江安吉与龙游两地的应用

Table 3 Case study in Anji and Longyou by GHI assessment.

应用地区	基础评价					综合评价结果
	气候状况	地质背景	环境地球化学质量	人类活动强度	总指数得分	
浙江安吉	70	92.5	76.5	85	78.16	良
浙江龙游	70	92.5	96.4	85	85.50	优

面积富硒土地，土壤硒含量最高达 0.742mg/kg[56]。虽然两地土壤 Se 含量均达到富硒标准，但同时存在 Cd、Ni 等重金属超标严重的问题。值得指出的是，安吉富硒区的农产品 Cd、Ni 也超标严重，而龙游富硒区则无此类现象。这是由于安吉富硒土地土壤呈酸性-弱酸性，Se 多被土壤黏粒吸附，活性较低。而龙游富硒区土壤继承了母岩中的 P、Ca、Mn、Zn 高背景，呈偏碱性-弱碱性，Se 活化度较高。且碱性环境对 Cd 具有固化作用，作物对 Cd 的吸收大大减少，有利于形成天然富硒农产品。因此，龙游地区地质环境的“环境地球化学”分指数得分远超安吉，达到最优级别。

对当地居民的健康状况调查发现，虽然安吉当地农产品 Cd 超标严重，但当地居民健康状况良好，未出现“痛痛病”、肾功能衰竭、骨质疏松，以及致畸、致癌、致突变等地方疾病，发硒、发锌含量高[57-58]。居民平均预期寿命达 81.44 岁，超过全国平均水平(78.2 岁)。有研究认为是 Se、Zn 对 Cd、Ni 产生了明显了拮抗和屏障作用，使当地居民免于遭受重金属毒害[59-60]。此外，当地居民普遍收入较高，居民有能力购买外来替代农产品，以避免本土高 Cd 食品的摄入。而且，浙江省医疗卫生服务体系完善，“健康浙江”建设居全国领先地位，是浙江人民健康的有力保障。综合多因素评价可知，安吉地区虽然处于黑色岩系地质背景，土壤发育具有高 Cd 的地球化学特征，但高 Se 和高 Zn 对居民健康具有一定保护作用，且在使用外来替代农产品的情况下，居民不但可以在一定程度上规避高 Cd 地质背景带来的健康风险，还能够利用高 Se 地质条件对健康的促进作用，提升居民整体健康水平。

4　结论

在全球社会经济高速发展的今天，人群健康与地质环境的关系更为复杂，单一的环境与人群健康的评价方法已难以适应健康影响因素日益复杂化的局面。本文提出地质健康指数法(GHI)对地质环境的健康适宜性进行评估，从环境地球化学、区域地质背景、气候状况及人类活动强度等多维度出发，开展了基于复合视角的地质环境健康适宜性评价指标体系与评价方法研究。GHI 评价方法可以用于区域地质环境评价与分区，评价结果可以为地球系统科学理论研究提供基础资料，为提升人群健康水平、建设宜居环境提供基于地学的对策与建议。

然而，该方法还存在一些明显的局限。主要在于：①没有对受众人群进行分组，比如按照性别、年龄等进行分组。实际上儿童和成人在污染物的致癌和非致癌效应上存在极大差异。②没有考虑时间因素。通常健康效应是需要 10 年甚至更长的时间才能在个体上有所体现，但由于系统环境的复杂性和人群特征的多样性，每项指标产生健康效应的时间并不统一，因此评价是基于各项指标已经产生健康效应的假设开展的。③没有对人群的实际使用情况进行确认，而是考虑一个普遍的一般性质的效应。例如居民实际使用的水和食物的量和调查得到的现状可能存在很大出入，从而使评价结果与实际情况出现偏差。

综上所述，本文将对 GHI 方法不断改进，通过纳入不同目标人群和实际暴露量等指标，使该方法在区域地质环境对人群健康的适宜性评价方面更具有空间分异性，能够最大地满足普通民众和管理层的不同需求。

Index System and Evaluation Method of Geological Environment Suitability for Human Health

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HIGHLIGHTS

(1) A comprehensive geological health index system (GHI) was proposed to evaluate the geological environmental suitability for human health on a composite perspective.

(2) The index system was developed considering multiple dimensions such as environmental geochemistry, regional geological background, climate conditions, and intensity of human activities, and weights of each indicator were assigned by analytic hierarchy procedure (AHP).

(3) Case studies in Anji and Longyou counties demonstrated reasonable GHI assessment results of the suitability of regional geological environment to population health.

(4) Similar geological background could result in a different human health response, indicating complicated affecting factors contributing to the health status of local people.

ABSTRACT

BACKGROUND: Human health is closely related to the geological environment. There're various geological environment factors affecting human health in a composite way. Geological background characteristics, including tectonic structure, lithologic features, and landform configuration shape the living conditions of human being. Climate conditions and the spatial and temporal variation characteristics influence the comfortable level for habitation. More importantly, the direct and indirect impacts of elements and chemicals in rock, soil, water, and air and biosphere on human health are comprehensive and significant. In addition, various human activities have increasingly influenced geological substances and geological processes since the Industrial Revolution, which together with natural geological factors contribute to the unique public health characteristics of a region. (Fig.1). Quantifying the impact of geological environment on human health has always been a hot topic in the study of environment, geology, and other disciplines. In terms of environmental health impact assessment, many scholars or organizations have developed different evaluation indicator systems from different research perspectives. Existing studies focus on assessing health risks from a single perspective, such as chemical substances or engineering construction, while comprehensive evaluation of the health impact of the geological environment from the perspective of the earth system is still rare. In today's world of rapid socio-economic development, the relationship between human health and geological environment is even more complex, and single methods of evaluating environmental and population health are increasingly inadequate to cope with the increasingly complex health factors. The study of the suitability of geological environment for human health is rapidly progressing under a new theoretical framework.

RESULTS: (1) The evaluation index system. A comprehensive geological environmental health suitability evaluation index system was developed based on a composite perspective, taking into account multiple dimensions such as environmental geochemistry, regional geological background, climate conditions, and intensity of human activities. The rock strata, topography, climate conditions, as well as the geochemical quality of multiple media such as soil, water, and crops in a certain area, shape the specific lifestyle and behavioral habits of the regional population, resulting in unique regional health characteristics.

(2) GHI evaluation method. The geological health index (GHI) evaluation method was established, which divides the health suitability of regional geological environments into five grades based on GHI scores: excellent (85 points or above), good (75-85), fair (60-75), poor (50-60), and very poor, representing the conditions of extremely suitable, suitable, moderately suitable, possibly suitable, and unsuitable for human health.

(3) Case study. A case study was conducted in Anji and Longyou counties of Zhejiang Province using the GHI method. The overall GHI scores of the two regions indicated that the health suitability of the geological environment in Anji county was rated as “good” (78.16), while Longyou county was rated as “excellent” (85.50). The evaluation results reflected the health suitability of the regional geological environment, and could provide guidance for rational utilization of geological resources beneficial to health and avoidance of geological risks adverse to health.

DISCUSSION: (1) Principles for choosing indicators. The assessment index system was established following scientific principles, making sure the indicators are representative for general geological environment and closely related to human health. The influence of each indicator on health should be based on evidence, which can objectively reflect the difference of geological environment on population health. Furthermore, the indicators should be available in most settings and be simple to calculate. It is beneficial to have the current environmental industry or health industry standards as a reference.

(2) Composition of the index system. The GHI index system included 15 specific indicators, which were listed in Table 1. Four sub-indexes were classified to represent the influencing factors of geological environment on human health, which were climate, geological background, environmental geochemistry characteristics and human activities. Two indicators of human comfort level, representing integrated influence of air temperature, humidity and wind, and incidence of extreme weather, were used to characterize the climate factors that affect human health. Four indicators, including regional crustal stability, natural environmental radioactivity, altitude and vegetation coverage, which were closely related to population health, were extracted to characterize the suitability of spatial characteristics of structure, rock, strata and epigenetic systems to population health. Seven indicators including environmental air quality, drinking water quality, irrigation water quality, cultivated land soil quality, agricultural product quality, water resource quantity and land resource quantity were used to characterize the environmental geochemical elements that have an important impact on population health. Human activities have influenced and changed the natural substances at global and regional scales, which have brought about significant impacts on the survival of organisms and human health. In this study, population density and per capita gross industrial and agricultural product were used to characterize the intensity of human activities.

(3) GHI evaluation method. The evaluation of the health suitability of the geological environment was performed following the processes of data standardization, weight assignment, index score calculation and evaluation level classification. A two-step method was proposed to standardize data processing to complete the evaluation process of health suitability of the geological environment. Firstly, the environmental quality level corresponding to all indicators was determined by comparing with the national average level, national and industrial standards and specifications. Secondly, the impact of different levels of geological environmental quality on population health was evaluated with reference to literature, world and national health standards, and the degree of impact is measured with 0-100 points. The weights were assigned to each indicator according to analytic hierarchy procedure (AHP). The scores of each sub-index and total GHI index were calculated according to corresponding equation. Finally, the health suitability of regional geological environment is divided into five levels: excellent (85 points and above), good (75-85), general (60-75), poor (50-60) and bad (below 50), which respectively represent the state of extremely suitable, suitable, relatively suitable, possibly suitable and unsuitable to population health in certain regional geological environment.

(4) Case study. A case study was conducted in Anji and Longyou counties of Zhejiang Province using the GHI method. The results showed that the two regions scored similarly in the three sub-indices of "climate conditions", "geological background", and "human activity intensity", while there was a significant difference in the sub-index of "environmental geochemistry". This was because the agricultural products in the selenium-enriched area of Anji were severely contaminated with heavy metals, while there was no such phenomenon in the selenium-enriched land of Longyou County. The overall GHI scores of the two regions indicated that the health suitability of the geological environment in Anji county was rated as "good" (78.16), while Longyou County was rated as "excellent" (85.50). However, the investigation found little difference in the health status of the residents in the two areas, with the average life expectancy of the residents in both areas higher than the national average. This suggests that although the geological environment in Anji County has high geochemical characteristics of Cd and Ni, the selenium-enriched environment has played a certain compensatory role, and Anji County still maintains an overall level of "suitable" for human health.

(5) Limitations and future research prospects. With the rapid development of global society and economy, the relationship between population health and geological environment is complicated, and the evaluation method with single dimension is difficult to adapt to the increasingly complicated situation of health influencing factors. In this study, the GHI method is proposed to evaluate the health suitability of geological environment. Based on the multi-dimension of environmental geochemistry, regional geological background, climate condition and human activity intensity, the evaluation index system and evaluation method of geological environmental health suitability are studied from a composite perspective. The GHI evaluation method could be used for regional geological environment evaluation and zoning, and the evaluation results could help manage a more habitable environment and improve the health level of the population. However, there are still some limitations to this approach: ①There is no grouping of the target population. ②The exposure time is not considered. ③The actual intake of water and food is not confirmed. To sum up, the method will be continuously improved by refining the index system, to develop a health suitability assessment method with greater spatial heterogeneity that could meet the needs of the public and government to the greatest extent.

KEY WORDS: geological environment; public health; suitability evaluation for human health; geological health index (GHI); assessment for environmental impact on human health

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