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水源涵养内涵及估算方法综述

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摘要：水源涵养和生态系统过程与人类生产生活紧密相关，深入研究水源涵养对维持生态系统健康和人类社会可持续发展至关重要，对促进人与水和谐共生具有指导意义。随着对水源涵养研究与应用的深入，水源涵养内涵逐渐丰富，评估方法愈加多样，但以往的研究中水源涵养定义模糊，缺乏对各种评估方法的综合性对比分析，因此急需明确界定水源涵养内涵，分析各种估算方法的适用性。采用文献分析法系统梳理水源涵养研究历程，将其划分为认识与萌芽期、理论发展期、定量计算和模型综合评估等 4 个阶段；从定义、水量与功能等 3 个方面明确界定水源涵养内涵，从原理、时空尺度、适用范围及优缺点方面对已有水源涵养量估算方法进行对比和分析，并展望水源涵养研究的未来发展方向。

关键词：水源涵养；定义；功能；计算方法；模型

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生态系统服务是指人们从生态系统中获取的所有直接和间接收益[1-2]，与人类福祉和社会可持续发展紧密相关，近年在国内外备受关注。当前水环境恶化和气候变暖造成日益严峻的水资源问题，水资源需求量的增加则加剧了水资源短缺[3]，与水有关的生态系统服务受到高度重视。由于水是连接各生态系统过程及人类活动的重要纽带，水源涵养在众多生态系统服务中占据中心地位，是表征生态系统状况的关键指标。水源涵养的变化不仅直接影响流域内自然要素状况与生态系统过程[4]，也会对下游地区的生态系统和水资源产生间接影响，引起新一轮的人水互动协同效应。因此，研究我国生态系统的水源涵养功能，明确不同区域水源涵养功能与生态系统过程和人类活动的关系，识别水源涵养重要区，对当地生态屏障优化、气候变化风险应对及下游地区水资源优化配置具有重要的现实意义，同时对缓解我国水资源问题、发展完善“人-土-水”最优布局、促进区域可持续发展与生态文明建设具有重要指导意义。

自 20 世纪以来，学者在我国开展了广泛的水源涵养功能研究，为全国水土综合管理和新时代生态文明建设作出了重要贡献。但不同学者所界定的水源涵养内涵不同，缺乏统一的标准，实际工作中采用的研究方法多样，致使水源涵养量的估算结果往往存在较大差异。因此，本文对水源涵养研究进行梳理、概括与总结，阐明水源涵养内涵，分析已有估算方法的有效性与适用性，以规范水源涵养评估过程，为我国水源涵养研究与生态文明建设提供指导。

1　水源涵养研究历程

1.1　认识与萌芽期

人类从农牧时代对水源涵养就有所认识，我国

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有明确文字记载的水源涵养是清朝梅曾亮1823年在《书棚民事》中的记述“每天雨，从树至叶，从叶至土石，历石罅，滴沥成泉。水缓，故低田受之不为灾，而半月不雨，高田犹受其浸溉”。该文分析了树木水源涵养对降水的截流、洪水削峰、基流增加及灌溉作用，此时人们初步认识到树木的水源涵养作用。水源涵养的研究起源于人们对森林与水关系的认识，可以追溯至19世纪。文献[5]提到1864年德国学者Ebmayer在巴伐利亚地区观测林区地表的蒸发，首次探究影响蒸发的因素，1879年又在奥地利观测森林对降水的截留量。1900年，在瑞士Bernese Emmental山区开展了2个集水区对比试验，以探究植被对集水区径流量的影响，揭开了试验森林水文学的序幕[6]。随后，众多国家开展了小流域对比试验，研究有林地和无林地水源涵养的差异[7-8]。文献[9-10]提到我国的森林水文研究起步较晚，始于20世纪20年代，罗德民和李德毅在我国多地开展了森林对径流和水土保持影响的观测研究。美国学者Kittredge[11]在1948年提出“森林水文学”的概念，推动了森林水文过程的研究，也为森林水源涵养功能的研究奠定了基础。从19世纪初至20世纪50年代可以看作水源涵养的认识与萌芽阶段，此时水源涵养的概念不明确，主要指森林对径流的影响，研究方法单一，主要利用观测数据来分析森林与水的关系。

1.2　理论发展期

20世纪60年代，美国学者Bormann等[12]在小集水区范围内研究森林生态系统与水文过程，首次将森林生态系统与水文学研究相结合。在20世纪70年代，森林植被对河流水质的影响得到关注，国外开展了森林对改善水质的研究，将净化水质视为水源涵养功能的一种表现形式[13]。与此同时，森林水文过程的研究得到重视，开展了林冠截留、枯落物持水、土壤蓄水与林地蒸散发等森林水文过程的研究，积累了大量的实测资料，发展了Rutter等[14]、Gash[15]林冠截留模型，出现众多计算枯落物持水量、土壤蓄水量、林地蒸散发量的经验公式，森林水文过程研究的发展丰富了水源涵养研究的理论基础。

20世纪六七十年代可以看作水源涵养研究的理论发展阶段，这一时期在森林水文学领域取得了众多研究成果，对林冠截留、枯落物持水、土壤蓄水等水文过程的认识愈加明确。但是，这一阶段的研究对象仅限于森林生态系统，仍将水源涵养视为森林水文过程的一部分，并未明确界定水源涵养概念[16]。

1.3　定量计算阶段

20世纪80年代以来，逐渐进入到水源涵养功能的定量评估阶段。早期主要实地测量林区不同作用层的降水截留率、土壤入渗率及蒸散发，在实测数据的基础上计算森林不同作用层的持水量[17]。1997年，Constanza等[18]定义了生态系统服务的概念，水源涵养开始作为生态系统的一项服务功能而受到关注。研究者[19-20]在实测数据的基础上估算了众多小流域范围内生态系统的水源涵养量及价值。由于学者对水源内涵的理解不同，在实际工作中采取的估算方法多样。典型方法有水量平衡法、降水贮存法、年径流法、地下径流增长法、林冠截留剩余法、土壤蓄水能力法、综合蓄水能力法、多元回归法以及影子工程法等。

20世纪80年代至21世纪初可以看作水源涵养研究的缓慢增长期，此时森林生态系统的水源涵养概念逐渐明确，涌现出众多水源涵养估算方法。但水源涵养量的估算主要集中在样地尺度或小流域范围，计算结果受观测数据影响较大，不同计算方法得到的结果相差较大，缺乏可比性。

1.4　模型综合评估阶段

近十余年来，国内外学者逐渐采用模型方法在区域范围内综合评估水源涵养功能，众多水文模型、生态模型广泛应用于水源涵养功能的研究中，如SWAT模型、InVEST模型、元胞自动机模型、SEBS和SCS模型、Terrain Lab模型等。与此同时，水源涵养的尺度问题受到关注，王晓学等[21]从不同时空尺度探讨了森林水源涵养功能的内涵，界定了不同时空尺度下的水源涵养功能。此外，水源涵养的内涵不断丰富，其研究对象也由单一的森林生态系统向草地[22-23]、湿地[24]、都市农业[25]等其他生态系统扩展。

总的来看，人们对水源涵养的认识处于动态发展的过程中，见图1。当前的水源涵养，研究内容更加综合，不仅关注流域内部的生态水文过程(降水截留、蒸散发等)，还研究多个水文过程与生态系统产生的综合效应(对降水的影响、调节气温等)；研究对象由森林扩展到其他陆地生态系统，对比不同生态系统水源涵养能力的差异；研究范围进一步扩大，在空间上由样地尺度发展到流域、区域尺度，在时间上研究年、月、日不同时间尺度及不同时间序列下水源涵养功能的动态变化；相

应的估算方法更加丰富,特别是采用众多综合模型评估水源涵养功能,对其进行更深层次的量化,同时注重结果的可视化表达,强调流域范围内水源涵养功能的空间差异性。

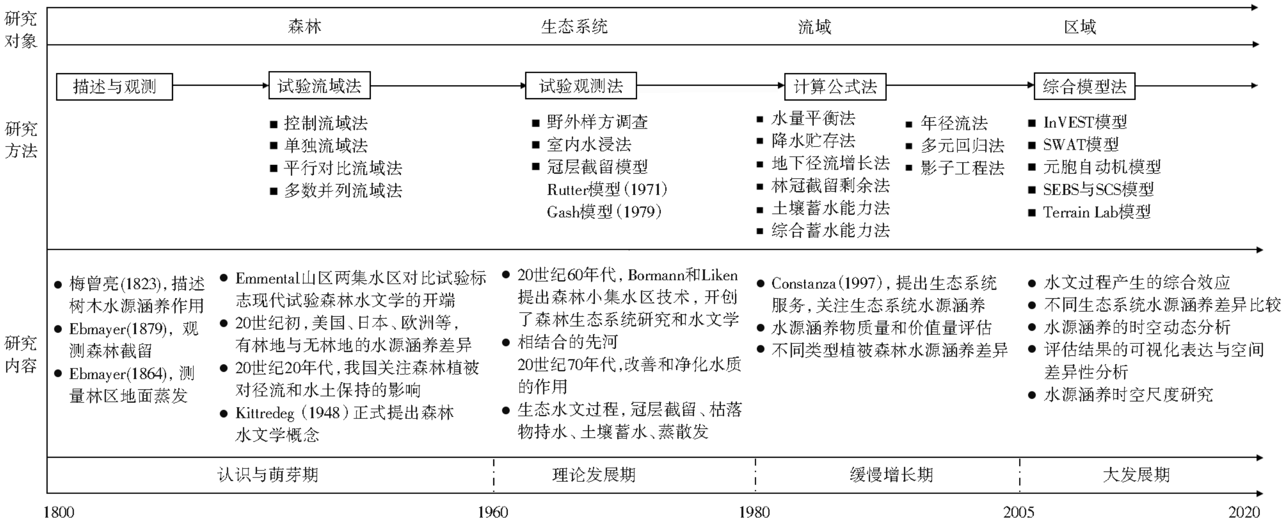

图 1　1823—2020 **年水源涵养内涵与计算发展历程**

2　水源涵养内涵界定

随着研究的深入,水源涵养内涵逐渐丰富,不同学者的理解不同,尚未形成统一的定义。研究的早期将水源涵养视为森林对河流径流量的影响[26]。随着森林水文过程研究的逐渐成熟,水源涵养内涵扩展为森林生态系统通过林冠层、枯落物层及土壤层截留和贮存降水,表现出补充地下水、调节河川径流等功能[27-29]。慢慢地,森林对降水的影响、净化水质的作用也视为水源涵养功能。这一时期水源涵养量定义为冠层截留、枯落物持水和土壤蓄水量三者之和,研究对象仅限于森林生态系统。如今,水源涵养的研究对象由森林生态系统扩展到具备涵养水源能力的区域,水源涵养量定义为某区域在一定时段内收入与支出水量之差[30-34]。总之,虽然不同学者界定的水源涵养内涵存在一定的重叠与差异,但基本都将水源涵养视为森林或草地、湿地生态系统对降水的截留贮存能力,以及在此过程中体现出的调节径流、水源供给与净化水质等功能。

综上所述,水源涵养可以从功能、对象、水量等 3 个方面界定其内涵。

水源涵养是指在一定时空范围内,生态系统通过林冠层、枯落物层和土壤层、湖泊、水库水体等对降水进行截留、下渗以及贮存等过程,将水分充分保持在系统中的过程和能力,不仅满足系统内部对水源的需求,并且可以向外部及中下游地区提供水资源,见图 2。

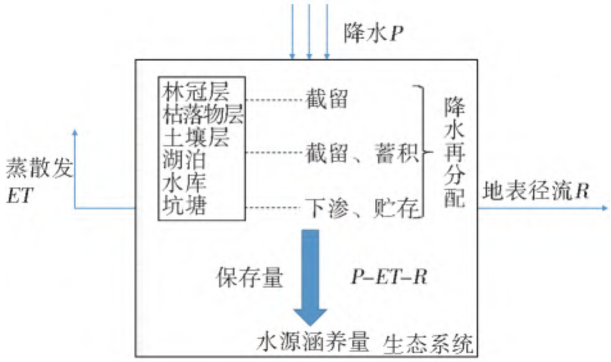

图 2　水源涵养过程

2.1　水源涵养功能

水源涵养功能指生态系统在涵养水源的过程中参与流域水循环、调节水文过程并产生生态效益的能力,对维持生态系统平衡至关重要,同时可提供众多调节和供给服务[35-36]。作为多时空尺度下生态系统与水文过程综合作用的结果,水源涵养功能涉及的载体、生态水文过程及时间尺度特征众多,而且表现形式多样。从表现形式来看,水源涵养功能主要有水源供给、调节径流、拦蓄洪水、净化水质、水土保持和调节局地气温等,见表 1。从水源涵养功能所涉及的载体、过程、表现形式及时间尺度特征来看,可以从狭义和广义的角度进行区分,见图 3。狭义的水源涵养功能是指涵养水源过程中森林-草地-土壤所形成的生态系统与水的相互作用,包括拦蓄洪水、调节径流、水源供给等;广义的水源涵养功能则包含了水文过程对局地气候、水土产生的综合影响与生态效益,不仅考虑森林-草地-土壤所形成的生态系统,还加入湖泊-水库-坑塘进行的水源涵养,不

仅包括了水源供给、调节径流及拦蓄洪水，还有净化水质、水土保持和调节局地气温等。

表 1　水源涵养功能表现形式

功能	解释
水源供给	稳定地提供水量供流域内部使用，多余的水分可提供给中下游地区，补给中下游地区的生态耗水、人类活动用水等
调节径流	水源涵养区可看作天然水库，在雨期储存降水、补充地下水、削减洪峰，在旱季补充河道水量，增加河流径流量
拦蓄洪水	降水事件中，不同作用层截留降水，改变暴雨产流过程，削减洪峰流量，延长洪水时间
净化水质	降水经过生态系统内部的层层截留，发生吸附过滤作用及一些物理化学过程，水质发生明显的改善，净化水质作用在森林中表现得最明显
水土保持	地表植被和枯落物对降雨吸收和缓冲，减缓了降雨对土壤表层的侵蚀和冲刷
调节气温	通过截留、贮存降水以及蒸散发等过程，参与流域水循环，对局地小范围内降雨量、温度和湿度产生影响

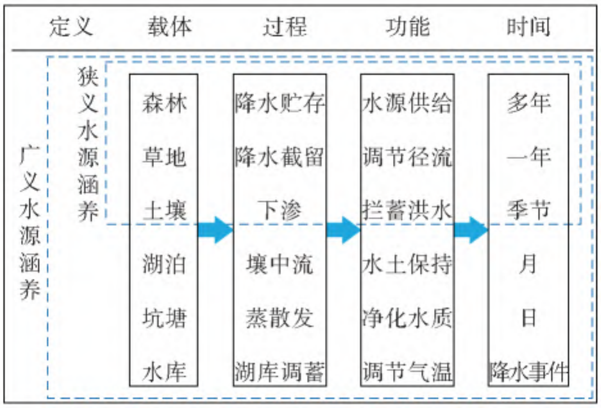

图 3　水源涵养功能界定

2.2　水源涵养量

水源涵养量是指某时段内生态系统存储的水量，其大小常用来评估水源涵养功能，其实质是指生态系统在一定的时空范围与条件下对降水的调蓄能力，即非雨期的蒸发与土壤产流量。在计算水源涵养量时应考虑时间尺度（场次降水、月、年），对于场次降水，其水量是降水减雨期蒸发与产流；对于月、年大时间尺度，其水量是总降水量减雨期蒸发和地表产流。水源涵养量可分为潜在水源涵养量与实际水源涵养量，前者指对生态系统充分供水情况下生态系统对降水的最大调蓄能力，后者指实际降水与气候条件下生态系统对降水的实际调蓄能力。潜在水源涵养量是实际水源涵养量的最大值。水源涵养量最小值是 0，出现在不透水地面情况，所有降水均被蒸发和地表产流；水源涵养量最大值是降水量，当地表植被覆盖度足够高或者直接降水到湖泊水库中，降水雨强与雨量达不到地表产流条件，所有降水均被滞蓄在生态系统中。

3　基于概念模型的水源涵养定量评估方法

水源涵养量评估即定量计算生态系统内存储的水量，与水源涵养内涵相适应。由于学者定义的水源涵养概念不同及研究区的差异性，实际工作中采取的计算方法多样，主要有水量平衡法、降水贮存法、年径流法、地下径流增长法、林冠层截留剩余法、土壤蓄水能力法、综合蓄水能力法及多元回归法等，每种方法都存在一定的优势、局限性与适用范围，见表 2。

上述方法大多从某一个维度来计算水源涵养量，不同方法所表征的水源涵养量有所差别，如：土壤蓄水能力法将土壤中贮存的水量视为水源涵养量，综合蓄水能力法将冠层截留量、枯落物持水量和土壤蓄水量三者之和视为水源涵养量，这使得不同方法得到的计算结果可比性差。综合蓄水能力法考虑了不同作用层涵养的水量，与水源涵养内涵较为接近，并且可对比不同作用层对总水源涵养量的贡献，应用范围相对较广[37-39]。水量平衡法将某区域在一定时段内收入水量与支出水量之差视为水源涵养量，与水源涵养内涵最为匹配，时空尺度适用性较强，是目前应用最广的方法[29,40-41]。聂亿黄[42]等将地表径流量视为水源涵养量，利用水量平衡法估算了青藏高原地区的水源涵养量，结果表明青藏高原地区多年（1982—2003 年）平均水源涵养量为 $3.451\ 29\times10^{11}$ m^3，东南部水源涵养量大，而西北地区水源涵养能力很弱。龚诗涵等[4]将降水量与地表径流量及蒸散发量的差视为水源涵养量，利用水量平衡法估算了全国生态系统的水源涵养量，结果表明 2010 年全国水源涵养总量为 12 224.33亿 m^3，在空间上呈现东南高西北低、由东到西递减的趋势。

水源涵养是生态系统与水文过程综合作用的结果，与生态系统类型、气候条件、下垫面性质及人类活动等多种因素有关，是一个复杂的综合性概念[41-42]，如何在多时空尺度下精确地计算水源涵养量仍然是当下研究的难点与重点。根据本文所界定的水源涵养内涵，水源涵养量应该是降水落到地面后扣除雨期蒸发与地表产流量均为地表生态系统（包含湖泊水库）的水源涵养量，建议采用具有物理

机制的水文模型计算水源涵养量。通过水文模型模拟出雨期实际蒸发（ET_1）与地表产流量（R_s）。水源涵养量 $W=P-R_s-ET_1$。非雨期的蒸散发、壤中流及土壤含水量均为水源涵养量的一部分。建议采用日尺度分布式水文模型计算水源涵养量，在一场完整的洪水或月、年等长时间尺度上，利用模型直接计算出雨期水源涵养量并在计算时段内求和即是总水源涵养量。

表 2　水源涵养计算方法

序号	方法	解释	公式	优缺点	适用范围	最适尺度	
						空间	时间
1	水量平衡法	降水量与蒸散发量之差[43-44]	$W=P-ET$	“黑箱”原理，公式简单，所需经验数据少；结果准确性受蒸散发值的影响较大，该法减去了蒸发中包含的部分水源涵养量，计算值偏小	空间差异较小的区域	所有尺度	所有尺度
		降水量与蒸散发量及其他消耗水量的差值[45]	$W=P-ET-R$				
2	降水贮存法	由森林蒸散发的历史观测值，确定树冠、树干、树木的蒸腾和扩散占降水量的比例，剩余部分为水源涵养量[46-47]	$W=\beta\times P\times\alpha$	公式简单，所需参数可由观测得到；忽略地表径流，蒸散发占降水比例难以准确计算	部分有经验常数的林区	所有尺度	月
3	年径流法	假设水源涵养量等于林区年径流量，不同土地覆盖类型每年消耗水量相等。水源涵养量为森林覆盖率与年径流量之积[48]	$W=\alpha\times R$	方法简便；未考虑林地与其他土地利用类型蒸散发的差别，计算误差较大	有森林覆盖的区域	流域尺度	年
5	地下径流增长法	森林可将地表径流转化为地下径流，有林区地下径流比无林区多。水源涵养量为有林区相比与无林区增加的地下径流量[49-50]	暂无统一的公式	所需参数较少，并且可由实地观测得到；忽视了林地地上部分的持水量，计算值偏小	有林地	所有尺度	月、年
6	林冠层截留剩余法	未被林冠截留而落到地面的水量为水源涵养量，用降雨量与林冠截留率计算[28]	$W=(1-\varphi)\times P$	涉及参数少，计算简单，可行性强；但未考虑地表径流和蒸散发，计算结果略大于实际值	森林覆盖率高的地区	所有尺度	所有尺度
7	土壤蓄水能力法	涵养的水分贮存在土壤中，水源涵养量为土壤非毛管孔隙度对降水的短期滞蓄量，可用土壤厚度和非毛管孔隙度相乘[10,20,51]	$W=10^4\times\lambda\times h$	方法简便，便于操作；但仅计算土壤贮存水量，忽略其他层拦蓄的水量和森林消耗水量	森立覆盖地区	所有尺度	所有尺度
8	综合蓄水能力法	冠层截留量、枯落物持水量和土壤蓄水量三者之和[37-38,52]	$W=I+K+Q$	分别计算林冠层、枯落物层和土壤层的涵养水量，可对比不同作用层的涵养能力；需要较多实测值，忽略森林蒸散发，计算结果是理论上的最大值	降水丰沛的地区	小流域尺度	所有尺度
9	多元回归法	根据下垫面特征和气象因子，得到计算水源涵养量的多元线性回归模型[53]	暂无统一的公式	充分考虑水源涵养的影响因子，逻辑缜密；但建模需要大量的实测数据，且模型难以推广	获取回归模型参数的地区	流域尺度	月、年

注：表中 W 为水源涵养量，mm；P 为降水量，mm；ET 为实际蒸散发量，mm；R 为地表径流量，mm；I 为冠层截留量，mm；K 为枯落物层持水量，mm；Q 为土壤层蓄水量，mm；β 为森林降水贮存量占降水量比率，%；α 为森林覆盖率，%；φ 为林冠截留率，%；λ 为土壤非毛管孔隙度，%；h 为土壤厚度，cm。

4　基于动力模型的水源涵养定量评估方法

随着对水源涵养理解的深入，以水文循环过程为理论基础，借助 GIS、RS 和计算机技术，发展了一系列水源涵养综合评估模型。水源涵养评估逐渐由上述传统计算方法发展到基于动力模型的综合评估方法，见表 3。这些模型能够实现水源涵养功能的动态模拟分析，已成为定量评价水源涵养功能的主要途径。模型可分为两大类：一类是传统的水文模型，以 SWAT 模型为代表；另一类是新兴的生态系统服务评估模型，以 InVEST 模型为代表[54]。水文模型侧重于水源涵养的驱动因素，更加关注水源涵养过程的模拟；新兴的生态系统服务评估模型，关注最终的生态系统服务及评估结果在景观尺度上的可视化表达。

表 3　水源涵养评估模型

模型	公式	尺度		优缺点
		时间	空间	
InVEST[45-55]	$R=\min\left(1,\frac{249}{V}\right)\cdot\min\left(1,\frac{0.9\times I_T}{3}\right)\cdot\min\left(1,\frac{K_{sat}}{300}\right)\cdot Y$ $Y=\left(1-\frac{ET_a}{P}\right)\cdot P$	年	30 m～10 km 的网格单元；流域	可视化、动态性强；但输入数据多，只能模拟年平均水源涵养量
SWAT[56-57]	$Q_1=\sum_{i=1}^{n}(P_i-ET_i-Q_{ij})A_i$	日，月，年	水文响应单元；流域	物理机制强，水文过程模拟准确，时间分辨率为日时间步长；模型参数的不确定性大，校正困难
元胞自动机模型[58]	$Q_2=\sum_{i=1}^{m}W_{(t+1)i}+D_{(t+1)}\bar{E}\cdot n_1\cdot\Delta t$	降水事件	水文响应单元；元胞单元	提供尺度上推的方法；模型只适用于降水季节(7—8 月)
SEBS 与 SCS 模型[41,59]	$R=P-ET-Q$ $E_{daily}=8.64\times10^7\overset{24}{\underset{0}{\Lambda}}\cdot\frac{R_n}{\lambda\rho_w}$ $Q=\frac{(P-0.2S)^2}{P+0.8S},P\geqslant0.2S$	年	区域	蒸散发和地表径流计算准确；未考虑损失的地下径流，结果偏大
Terrain Lab[60-61]	暂无统一的公式	日	网格单元；流域	考虑植被-土壤系统垂直方向的差异性，水文参数计算准确；实际应用中需进行水量平衡验证

注：表中 R 为水源涵养量，mm；V 为流速系数；I_T 为地形指数；K_{sat}为土壤饱和导水率，cm/d；Y 为产水量，mm；ET_a 为实际蒸散发量，mm；P 为降水量，mm；Q_1 为水源涵养总量，m^3；ET 为蒸散发量，mm；Q 为地表径流量，mm；A 为水文响应单元的面积，km^2；i 表示第 i 个水文响应单元(或元胞单元)；n 为水文响应单元的总个数；j 为不同时间尺度(年、月、日)所对应的值；Q_2 为(t+1)时刻森林涵养水源总量，mm；$\bar{E}$ 为饱和林冠的平均蒸发速率，mm；$W_{(t+1)}$ 为(t+1)时刻元胞单元水库涵养水源量，mm；$D_{(t+1)}$ 为(t+1)时刻向深层土壤的渗漏量，mm；m 表示所模拟区域的元胞单元的总数；n_1 为模拟次数；Δt 为时间步长；E_{daily}为实际日蒸散量，mm；$\overset{24}{\underset{0}{\Lambda}}$ 为日蒸散比；ρ_w 为水的密度，kg/cm^3；R_n 为地面净辐射通量，W/m^2；S 为流域当时的可能滞留量，mm。

4.1　InVEST 模型

生态系统服务与权衡综合评估模型(InVEST，the integrate valuation of ecosystem services and tradeoffs tool)由美国斯坦福大学、世界自然基金和大自然保护协会联合开发，是评估生态服务的有效工具，能够以定量化、价值化和可视化的方式表达生态系统服务，并预测未来情景下的生态服务。Nelson 等[55]将 InVEST 模型应用于美国威拉米特河流域，模拟预测了不同土地利用/覆盖情景下生态服务(水质、土壤保持、碳储量)、生物多样性保护和商品生产水平的变化，为当地自然资源的管理和开发利用提供决策依据。此后，国内外众多学者使用 InVEST 模型评估了不同地区的多种生态系统服务[62-64]，并探讨了模型的敏感性与适用性，结果表明该模型在不同区域均有较好的模拟效果[65-66]。

InVEST 模型由众多子模块组成，其中的产水量模块是与水相关的生态服务评估的重要组成部分，常用于计算生态系统的水源涵养量[67]，能够体现区域范围内水源涵养功能的空间差异，目前已在美国、西非以及中国的黄土高原、三江源、北京山区等地区进行了应用，并取得了良好的模拟效果[30,68-72]。产水量模块以水量平衡为基本原理，通过 Budyko 理论[73]计算实际蒸散发，在此基础上计算栅格单元的产水量，其定义为降水量减实际蒸散发量。然后根据地表特征对产水量值进一步修正，得到最终的水源涵养量，主要计算公式见表 3。

InVEST 模型是目前应用最广泛的水源涵养评估模型，具有独特的优势性，但也存在一定的局限

性。主要优势有：以地图的形式展现水源涵养量的空间分布特征，有助于分析区域内水源涵养功能的空间差异，识别水源涵养重要区；InVEST 模型可以评估水源涵养、土壤保持、碳储量等多种生态系统服务，综合评估与权衡多种生态系统服务，为生态保护与资源管理提供决策依据[74]；模型的动态性强，可以预测不同土地利用/覆盖情景、气候情景下的水源涵养量[75]。主要局限有：在计算产水量时忽略了地表径流和土壤水之间的动态作用，计算结果存在一定的误差；时间尺度为年，不能反映水源涵养量的年内及洪枯水期变化特征；产水量模块需要输入较多栅格数据和生物物理参数，对输入数据敏感，结果精度受输入数据影响较大[76]。

4.2　SWAT 模型

SWAT(soil and water assessment tool)模型是美国农业研究部研发的分布式水文模型，用于分析和预测复杂流域内水文过程的长期变化，该模型物理机制强，能精确模拟分析蒸散发、径流、土壤水和基流等水文过程的时空变化[56]。目前已经在加拿大、北美寒区和中国的黑河、三江源等地区广泛应用，取得了较好的模拟效果[77-79]。

在 SWAT 模型中，首先将流域划分为子流域，然后根据地表特征将子流域划分为水文响应单元(HRU)[80]。以水文响应单元为最小模拟单元，进行蒸散发、地表径流、地下水、土壤水等过程的模拟[76]，将水源涵养量定义为降水量减蒸散量及其他消耗水量之差。

SWAT 模型可以计算空间上不连续分布景观的水源涵养量[57]，揭示不同植被类型水源涵养能力的差异。此外，模型可以分析年、月、日不同时间尺度上的水源涵养量，日尺度可以分析短期洪水的变化量，月尺度可以研究径流年内变化，分析调节径流功能，年尺度可以研究水源供给的能力。但模型校正困难，受参数影响大。

4.3　其他模型

除上述 InVEST 模型和 SWAT 模型外，还有学者依据自身对水源涵养内涵的理解提出一些计算模型，如王晓学等[58]提出了基于元胞自动机的森林水源涵养量计算模型，能够计算森林生态系统在不同空间、时间尺度上的水源涵养量，提供了由小尺度上推到大尺度的计算方法。但由于计算复杂，目前尚未推广应用。聂忆黄[41]、张海博[59]将 SEBS 蒸散发模型和 SCS 径流估算模型相结合来计算水源涵养量，蒸散发和地表径流计算较为准确，但未考虑地下径流部分，最终计算的水源涵养量比实际值偏大。

一些分布式水文模型也用于水源涵养量的计算中，这些水文模型多侧重于对水文循环过程的模拟，计算蒸散发、地表径流、土壤水等，在此基础上结合水量平衡原理得到流域水源涵养量，如 Terrain Lab 模型。Terrain Lab 模型是在 Wigmosta 等[81]提出的分布式水文-植被模型的基础上发展而来的，以像元为单位进行水文过程的模拟，可以计算实际蒸散发、土壤含水量及土壤湿度等水文过程参数[60-61]。Terrain Lab 模型充分考虑了植被-土壤系统在垂直方向的特征，对水文过程参数的模拟准确，适用于森林生态系统水源涵养量的计算。但模型缺乏流域范围内水量平衡的验证，实际应用中需要进行验证。

5　水源涵养价值评估

水源涵养作为生态系统一项重要的服务功能，为人们提供众多生态效益，是生态系统服务评估的一项重要内容。水源涵养价值评估就是从货币价值的角度出发，将生态系统的水源涵养能力进行价值化表达，常用于不同生态服务之间的权衡分析、生态系统服务总价值核算以及生态补偿中。一般是在水源涵养物质量计算的基础上，采用各种方法将生态系统涵养的水量换算为价值，用价值大小评价水源涵养功能[82-84]。目前多采用替代的方式间接计算水源涵养价值，影子工程法是应用最广泛的方法。此外，姜文来[85]从构成水资源价值因素的角度出发，提出了计算森林水源涵养价值的模糊数学模型。

5.1　影子工程法

影子工程法又称替代工程法，其原理是将生态系统视为天然水库，假定存在一个与生态系统水源涵养能力相同的工程(人工水库等)，那么此工程的修建费用或价值即可用来替代生态系统的水源涵养价值，将工程的修建费用或价值视为影子价格，水源涵养总物质量与影子价格相乘即水源涵养价值[1,86-87]见式(1)：

$$V=W\times P_0 \qquad (1)$$

式中：V 为水源涵养价值，元；W 为水源涵养总量，m^3，上文的水源涵养量乘以研究区面积即为此处水源涵养总量；P_0 为影子价格，元/m^3。

影子工程法计算水源涵养价值重点在于：水源涵养物质量的准确计算；选取合适的影子价格。水源涵养物质量的计算方法众多，前文已经讨论过。影子价格的选取方式不统一，总结起来主要有以下几种[88]：水库工程的修建成本，通常采用单位库容

水库的造价；供用水的商品价格；电能生产成本；级差地租；水资源的跨区域运费；海水淡化费用。其中，实际应用中使用最多的是前 2 种方法。

在早期的研究中，研究者在利用影子工程法计算水源涵养价值时，常选用单位库容造价 0.67 元/m^3 作为影子价格。例如：欧阳志云等[1]采用水量平衡法和影子工程法分析了我国陆地生态系统涵养水源的经济价值，结果表明涵养水源价值为 2.71×10^{11} 元/a。邓坤枚等[28]采用林冠截留剩余法和影子工程法评估了长江上游森林生态系统的水源涵养功能，算得水源涵养经济价值为 $1\,606.179\times 10^{8}$ 元/a，表明当地森林有巨大的水源涵养效益。刘敏超等[51]从凋落物和土壤层的蓄水能力角度研究三江源地区生态系统的水源涵养能力，并使用影子工程法计算水源涵养价值，结果表明三江源区水源涵养总价值为 $1.103\,4\times 10^{10}$ 元/a。

随着社会与经济的发展，依旧选取 0.67 元/m^3 作为单位库容造价显然不符合实际，近些年来，研究者在选取影子价格时结合当下经济发展状况，选取的影子价格更合理。例如：赖敏等[40]在评估三江源区水源涵养功能时，使用 InVEST 模型和影子工程法计算水源涵养价值，选用单位库容造价 7.02 元/m^3 作为影子价格，算得 2008 年三江源区水源涵养价值为 1.07×10^{11} 元。刘菊等[89]使用 InVEST 模型和影子工程法评估岷江上游生态系统水源涵养能力，选用供水价格 0.83 元/m^3 作为影子价格，结果表明 2010 年岷江上游水源涵养总量为 49.19 亿 m^3，水源涵养价值为 40.83 亿元。

影子工程法作为估算水源涵养价值的一种有效方法，其理论基础完备，实际应用中可操作性强，在我国水源涵养价值评估中广泛应用。但影子价格的选取方法众多，选取标准的不同使同一研究区的计算结果也可能存在较大差异，导致结果的可比性差。此外，在确定影子价格时应结合社会经济发展现状，考虑当下的水库修建成本与水资源价格，选取更加符合实际的影子价格。

5.2　森林水源涵养价值模糊数学模型

除上述应用广泛的影子工程法之外，姜文来[3]提出了计算森林水源涵养价值的模糊数学模型，见式(2)和式(3)。模型将森林水源涵养价值系统视为复杂的模糊系统，充分考虑构成水源涵养价值的 3 类因素：自然因素、社会因素和经济因素，从理论方面来看能准确计算森林涵养水源的经济价值。但由于模型考虑的因素众多，在实际应用中较难操作，目前很少应用，有待进一步发展。

$$V=(A\times \boldsymbol{R})\times \boldsymbol{S} \tag{2}$$

$$\boldsymbol{S}=(P,P_1,P_2,P_3,0) \tag{3}$$

式中：V 为森林水源涵养价值；A 为要素评价的权重值；$\boldsymbol{R}$ 为影响森林水源涵养单要素评价矩阵组成的综合评价矩阵；$\boldsymbol{S}$ 为水资源价格向量。

6　结论与展望

本文在分析水源涵养已有研究成果的基础上，主要得出如下结论。

(1)水源涵养研究历程可划分为 4 个阶段：认识与萌芽期(1800—1950 年)，主要基于观测数据分析森林与水的关系，将水源涵养视为森林对河流流量的影响；理论发展期(1960—1970 年)，对林冠截留、枯落物持水、土壤蓄水等过程的认识逐渐深入；定量化计算阶段(1980—2000 年)，水源涵养概念逐渐明确，水源涵养量估算方法得到空前发展；模型综合评估阶段(近十余年)，主要采用综合模型评估区域范围内的水源涵养功能。

(2)水源涵养是指在一定时空范围内，生态系统通过植被层、枯落物层和土壤层、湖泊、水库水体等对降水进行截留、下渗以及贮存等过程，将水分充分保持在系统中的过程与能力，不仅满足系统内部对水源的需求，同时向外部及中下游地区提供水资源。

(3)水源涵养功能是一个动态发展中的概念，其内涵不断丰富扩展，可以从狭义和广义的角度进行区分。狭义的水源涵养功能是指涵养水源过程中森林-草地-土壤所形成的生态系统与水的相互作用，包括拦蓄洪水、调节径流、水源供给等；广义的水源涵养功能则包含了水文过程对局地气候、水土产生的综合影响与生态效益，不仅考虑森林-草地-土壤所形成的生态系统，还加入湖泊-水库-坑塘进行的水源涵养，不仅包括了水源供给、调节径流及拦蓄洪水，还有净化水质、保持水土和调节局地气温等。

(4)水源涵养评估可以从物质量和价值量两方面展开，相关的计算方法和评估模型众多，每种方法都存在一定的优缺点、时空尺度、适用范围等，实际应用中需灵活选择评估方法。

已有研究存在如下不足：

(1)水源涵养内涵不统一。不同的研究者给出自己的水源涵养内涵，然后根据内涵给出水源涵养量的计算公式，计算的结果即使在同一时段同一区域也会有很大差异。

(2)水源涵养量计算对象不全。现有的计算仅

仅考虑植被土壤的水源涵养量，而忽略了湖泊水库坑塘在水源涵养中的贡献。在青藏高原大量内陆湖区域会存在很大的计算不确定性。

（3）水源涵养量计算中水循环过程过于简化。水源涵养量计算时多采用年与月尺度进行简化计算，水量平衡考虑不足，导致各个水文要素计算存在很大的不确定性。水源涵养计算时很多是降水减蒸发与径流。由于非雨期的蒸发与壤中流应该是水源涵养的部分水量，简单重复计算很可能会出现负值，显然不合理。

针对以上的不足，水源涵养研究与应用的核心发展方向是“统一标准，完善对象，加强水循环，耦合多模型，实现精准水源涵养计算”。可从以下 5 个方面开展进一步深入的研究：

（1）统一水源涵养的概念和内涵。基于水源涵养的发展与机理的研究，深挖水源涵养的内涵，给出合理的水源涵养定义，根据定义统一评价指标，规范水源涵养功能评估。

（2）完善水源涵养的研究对象。水源涵养不仅仅需要考虑植被、土壤，更应该考虑冻土、湖泊、坑塘和水库的蓄水功能，所以在计算水源涵养时，需将研究区域中植被、土壤、冻土、湖泊、坑塘、水库、河道作为研究对象，进行综合考虑，从而减小水源涵养计算的不确定性。

（3）加强水循环计算，实现多模型的耦合。利用最新发展的分布式水文模型，精确计算研究区域（或流域）的水循环过程，为获得更高精度的水源涵养提供准确的水文要素。生态模型、水文模型、湖泊模型、冻土模型的耦合能够更加综合地研究水源涵养，同时弥补单一模型的不足，以更加系统的视角看待水源涵养。

（4）气候变化和土地利用变化情景下水源涵养的预测。已往研究表明气候变化和土地利用变化是影响水源涵养功能的重要因素，合理预测水源涵养功能有助于水资源的综合管理和决策，应对未来变化和防范风险。

（5）加强区域相关性研究。当下的研究主要关注单一流域内的水源涵养功能，而很少考虑上游水源涵养区的变化对中下游生态系统、水量与人类活动产生的影响，加强区域相关性研究能够更好地发挥水源涵养作用。

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Review on connotation and estimation method of water conservation

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Abstract: Water conservation is closely related to ecosystem processes, production and life of human beings. In-depth research of water conservation is of guiding significance for promoting harmonious coexistence between humans and water and is vital to the health of ecosystems and the sustainable development of human society. With the deepening of the research and application of water conservation, its connotation is gradually enriched, and the evaluation methods become more diverse. However, the definition of water conservation in previous studies is vague, and the comprehensive comparative analysis of various evaluation methods is lacking. Therefore, it is urgent to define the connotation of water conservation and analyze the applicability of its various estimation methods. The history of water conservation research is reviewed by literature analysis, which can be divided into four stages: cognition and germination stage, theory development stage, quantitative calculation stage, and comprehensive model evaluation stage. On this basis, the connotation of water conservation is clearly defined from three aspects of definition, water quantity, and function. The existing estimation methods of water conservation are collected and sorted out, and systematic comparative analysis is carried out on the principles, time and space scales, the application scope, and advantages & disadvantages. The possible research direction on water conservation in the future was also put forward.

Key words: water conservation; definition; function; calculation method; model

Ecosystem services refer to all the direct and indirect benefits that people obtain from ecosystems [1-2]. They are closely related to human well-being and social sustainable development and have attracted much attention in recent years. Currently, the deterioration of the water environment and climate warming have caused increasingly serious problems of water resources, and the increase in water demand has intensified water shortage [3]. Thus, great importance has been attached to water-related ecosystem services. Since water is an important link between ecosystem processes and human activities, water conservation occupies a central position among many ecosystem services and is a key indicator to characterize the condition of ecosystems. The changes in water conservation not only

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directly affect the condition of natural elements and ecosystem processes in the basin [4] but also have indirect effects on ecosystems and water resources in downstream areas, causing a new round of synergistic effect of human-water interaction.

Studying the water conservation function of the ecosystem in China, clarifying the relationship between water conservation function and ecosystem processes & human activities in different regions, and identifying the important water conservation areas are of great practical significance for the optimization of local ecological barriers, coping with climate change risks, and optimizing water resources allocation in downstream areas. It is also of importance for alleviating China′s water resources problems, developing and improving the optimal layout of "human-soil-water", and promoting regional sustainable development and ecological civilization construction.

Since the beginning of the 20th century, scholars have carried out extensive research on the function of water conservation in China, making important contributions to the integrated management of water and soil and the national ecological civilization construction in the new era. However, the connotation of water construction defined by different scholars differs and lacks a unified standard, and the research methods used in practical work are diverse. As a result, the estimation results of water conservation capacity vary greatly. Therefore, this paper sorts out and summarizes water conservation research, clarifies the connotation of water conservation, and analyzes the validity and applicability of existing estimation methods in the hopes of standardizing the water conservation evaluation and providing guidance for water conservation research and ecological civilization construction in China.

1 Research history of water conservation

1.1 Cognition and germination stage

Humans have been aware of water conservation since the age of agriculture and animal husbandry. There is a clear written record of water conservation in China. It is the description of Mei Zengliang of the Qing Dynasty in 1823 in his Shu Peng Min Shi. "Whenever it rains, the rain flows from the trees to the accumulated fallen leaves, and then seeps from the leaves to the soil and rocks, passing through the cracks between the rocks and accumulating drop by drop into a spring. The water flows slowly, so it flows to the fields below without causing disaster. Even if it does not rain for half a month, the fields higher up still could be watered." In his paper, the effects of water conservation of trees on precipitation interception, flood peak elimination, base flow increase, and irrigation were analyzed, in which case the water conservation effects of trees were first recognized. The research on water conservation originated from the understanding of the relationship between forests and water, which could be dated back to the 19th century. Reference [5] mentioned that the German scholar Ebmayer first investigated the factors affecting evaporation by observing evaporation from the forest surface in the Bavarian region in 1864, and then observed the interception of precipitation by forests in Austria in 1879. In 1900, the comparative experiments on two catchment areas were conducted in the Bernese Emmental region in Switzerland to investigate the effect of vegetation on runoff in the catchment areas, which became the start of the experiment on forest hydrology [6]. Subsequently, comparative experiments in small basins were carried out in numerous countries to reveal the differences in water conservation between forest lands and non-forest lands [7-8]. As mentioned in references [9-10], the study on forest hydrology in China started relatively late in the 1920s, when Luo Demin and Li Deyi conducted observational studies on the effects of forests on runoff and soil & water conservation in several places in China. The American scholar Kittredge [11] proposed the concept of forest hydrology in 1948, which promoted the study on forest hydrological processes and laid the foundation for the study on the water conservation function of forests. The beginning of the 19th century to the 1950s can be regarded as the cognition and germination stage. In this period, water conservation was not defined clearly, which mainly referred to the influence of forests on runoff, and the research method was single, namely analyzing the relationship between forests and water mainly according to the observed data.

1.2　Theory development stage

In the 1960s, the American scholars Bormann et al.[12] studied forest ecosystems and hydrological processes in small catchment areas and combined forest ecosystems with hydrological studies for the first time. In the 1970s, the influence of forest vegetation on river water quality received attention, and studies on water quality improvement by forests were carried out in other countries, in which water purification was considered as a manifestation of water conservation functions[13]. Meanwhile, importance was attached to the study on forest hydrological processes, and the studies on forest hydrological processes such as forest canopy interception, water retention of litter, soil water storage, and forest evapotranspiration were carried out, through which a large number of measured data were obtained. The forest canopy interception models of Rutter et al.[14] and Gash[15] were established. Numerous empirical formulas for calculating the amount of water held in litter, soil water storage, and evapotranspiration from forest lands were developed. The development of forest hydrological process studies enriched the theoretical basis of water conservation research.

The 1960s and 1970s can be regarded as the theory development stage of water conservation research, during which numerous study results were achieved in the field of forest hydrology and the understanding of hydrological processes such as forest canopy interception, water retention of litter, and soil water storage became clearer. However, the object of study at this stage was limited to the forest ecosystem, and the water conservation was still considered as part of forest hydrological processes, without a clear concept of water conservation[16].

1.3　Quantitative calculation stage

The quantitative calculation stage of water conservation research began in the 1980s. In the early stage, the precipitation interception rate, soil infiltration rate, and evapotranspiration of different action layers in forest areas were mainly measured in the field, and the water-holding capacity of different action layers in the forest was calculated on the basis of the measured data[17]. In 1997, Constanza et al.[18] defined the concept of ecosystem services and water conservation started to receive attention as a service function of ecosystems. Researchers[19-20] estimated the amount and value of water conservation in ecosystems of numerous small basins with measured data. The estimation methods adopted in practice are diverse due to the different understandings of scholars on the connotation of water sources. The typical methods include water balance method, precipitation storage method, annual runoff method, underground runoff growth method, canopy interception method, soil water storage capacity method, comprehensive water storage capacity method, multiple regression method, and alternative engineering method.

The period from the 1980s to the beginning of the 21st century can be regarded as a slow growth period for the study of water conservation, during which the concept of water conservation in forest ecosystems was gradually clarified and many water conservation estimation methods emerged. However, the estimation of water conservation was mainly focused on the scale of sample plots or small basins. The calculation results were greatly influenced by the observed data, and the results obtained with different calculation methods varied greatly and lacked comparability.

1.4　Comprehensive model evaluation stage

In the past decade or so, scholars in China and other countries gradually adopted modeling methods to comprehensively assess water conservation function on a regional scale, and many hydrological and ecological models were widely used in the study of water conservation function, such as soil and water assessment tool (SWAT) model, integrated valuation of ecosystem services and trade-offs tool (InVEST) model, cellular automata model, SEBS and SCS model, and Terrain Lab model. Meanwhile, the scale problem of water conservation has received attention. Wang et al.[21] explored the connotation of water conservation functions of forests from different spatiotemporal scales and defined the functions of water conservation on different spatiotemporal scales. In addition, the connotation of water conservation was enriched, and its objects of study were expanded from a single forest ecosystem to other ecosystems such as grasslands [22-23], wetlands [24], and urban agriculture [25].

In general, the cognition of water conservation is in a dynamic development process (Fig. 1). At present, the studies of water conservation are more comprehensive, focusing not only on ecological hydrological processes within the basin (precipitation interception, evapotranspiration, etc.) but also on the combined effects of multiple hydrological processes and ecosystems (effects on precipitation, regulation of temperature, etc.). The objects of study are expanded from forests to other terrestrial ecosystems, and the differences in water conservation capacity of different ecosystems are compared. The spatial scope of the study is further expanded from the sample plot scale to basin and regional scales, and the dynamic changes of water conservation function are investigated on different time scales of year, month, and day and different time series. The corresponding estimation methods become more abundant, especially the use of numerous comprehensive models to assess the water conservation function and quantify it at a deeper level. In addition, research also focuses on the visual representation of the results, which can demonstrate the spatial differences of the water conservation function on the basin scale.

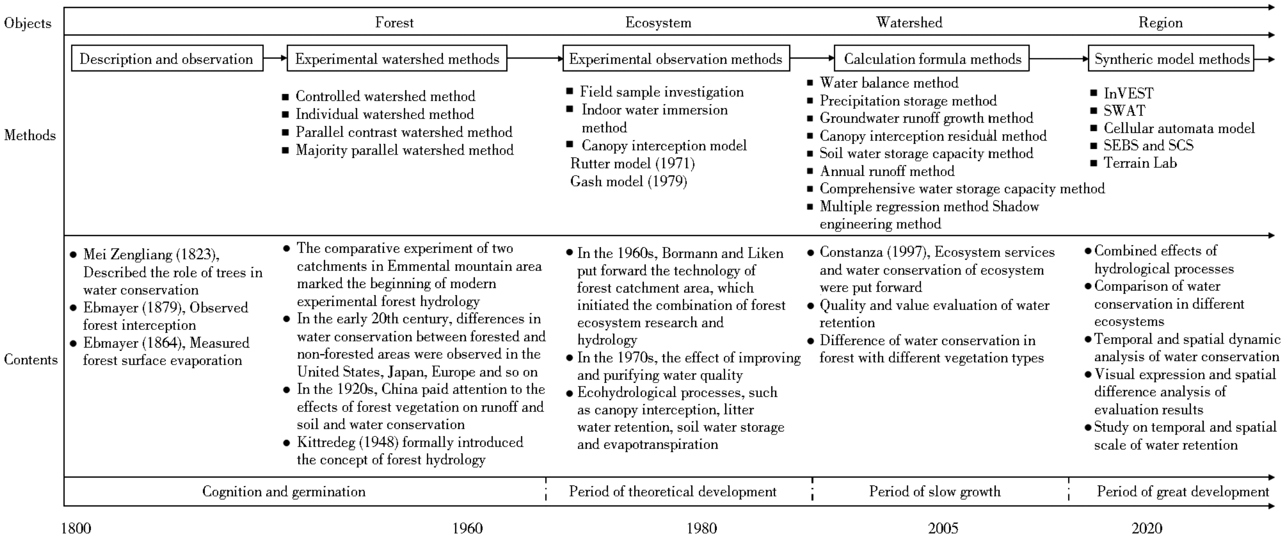

Fig. 1 Evolution of connotation and calculation of water conservation from 1823 to 2020

2 Connotation definition of water conservation

With the deepening of study, the connotation of water conservation has been gradually enriched, and different scholars have different understandings about it and have not yet formed a unified definition. In the early stage of research, water conservation was regarded as the influence of forests on river runoff [26]. As the research on forest hydrological processes gradually became mature, the connotation of water conservation was extended to the functions of forest ecosystems in retaining and storing precipitation through the canopy layer, litter layer, and soil layer, which exhibited the functions of groundwater replenishment and regulation of river runoff [27-29]. Later, the influence of forests on precipitation and their ability to purify water quality were also considered as water conservation function. In this period, the water conservation capacity was defined as the sum of canopy interception, water retention of litter, and soil water storage, and the object of study was limited to the forest ecosystems. Nowadays, the research on water conservation has been extended from forest ecosystems to areas with the capacity to retain water, and water conservation capacity is defined as the amount difference between the water received and the water consumed in a given area over a period of time [30-34]. In conclusion, although there are some overlaps and differences in the connotation of water conservation defined by different scholars, water conservation is regarded as the ability of forests or grasslands or wetland ecosystems to retain and store precipitation and the functions of runoff regulation, water supply, and water purification in this process.

In summary, water conservation can be defined from three aspects: function, object, and quantity.

Water conservation refers to the process and ability of ecosystems to retain water in the systems by intercepting, infiltrating, and storing precipitation through the canopy layer, litter layer, soil layer, lake, and reservoir in a certain spatiotemporal range. It not only meets the demand for water sources within the systems but also provides water resources to the outside and middle/lower reaches (Fig. 2).

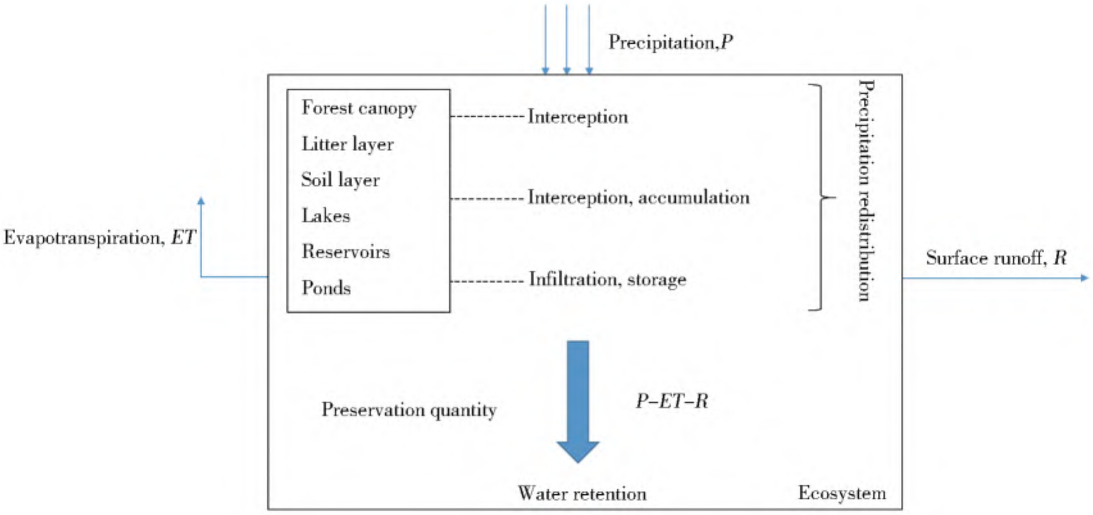

Fig. 2 Process of water conservation

2.1 Functions of water conservation

Functions of water conservation refer to the ability of ecosystems to participate in the basin's hydrological cycle, regulate hydrological processes, and generate ecological benefits in the process of water conservation, which are crucial to ecosystem balance and can provide numerous regulation and supply services as well [35-36]. As a result of the synthetic action of ecosystems and hydrological processes on multiple spatiotemporal scales, the functions of water conservation involve numerous carriers, ecological hydrological processes, and time-scale characteristics and are presented in various forms. In terms of manifestation forms, the functions of water conservation mainly include water supply, runoff regulation, flood storage, water purification, soil and water conservation, and local temperature regulation (Tab. 1). In terms of the carriers, processes, manifestation forms, and time-scale characteristics involved in the functions of water conservation, they can be distinguished in a narrow and broad sense (Fig. 3). The functions of water conservation in a narrow sense refer to the interaction of the ecosystems formed by forests, grasslands, and soils with the water in the water conservation process, including flood storage, runoff regulation, and water supply. The functions of water conservation in a broad sense include the comprehensive influence and ecological benefits of hydrological processes on local climate, water, and soil. Not only the ecosystems formed by forests, grasslands, and soils are considered, but also the water conservation by lakes, reservoirs, and ponds is involved. The functions include water purification, soil and water conservation, and local temperature regulation in addition to water supply, runoff regulation, and flood storage.

Tab. 1 Forms of water conservation functions

Function	Explanation
Water supply	Water conservation supplies water sources stably for use in the basin, and excess water can be provided to the middle and lower reaches to replenish water consumed by ecological processes and human activities there
Runoff regulation	Water conservation areas can be regarded as natural reservoirs, storing precipitation, replenishing groundwater, and reducing flood peaks during the rainy season, and replenishing river water and increasing river runoff during the dry season
Flood storage	During precipitation events, different action layers intercept precipitation, change the storm runoff process, reduce flood peak flow, and prolong flood time
Water purification	Precipitation is retained by layers within ecosystems, which results in significant improvement in water quality through adsorption, filtration, and some physicochemical processes, with water purification being most evident in forests
Soil and water conservation	Surface vegetation and litter absorb and buffer rainfall, slowing down the erosion and scouring of the soil surface by rainfall
Temperature regulation	Ecosystems participate in the basin's hydrological cycle through precipitation interception, precipitation storage, and evapotranspiration, which can affect the amount of rainfall, temperature, and humidity on a small local scale

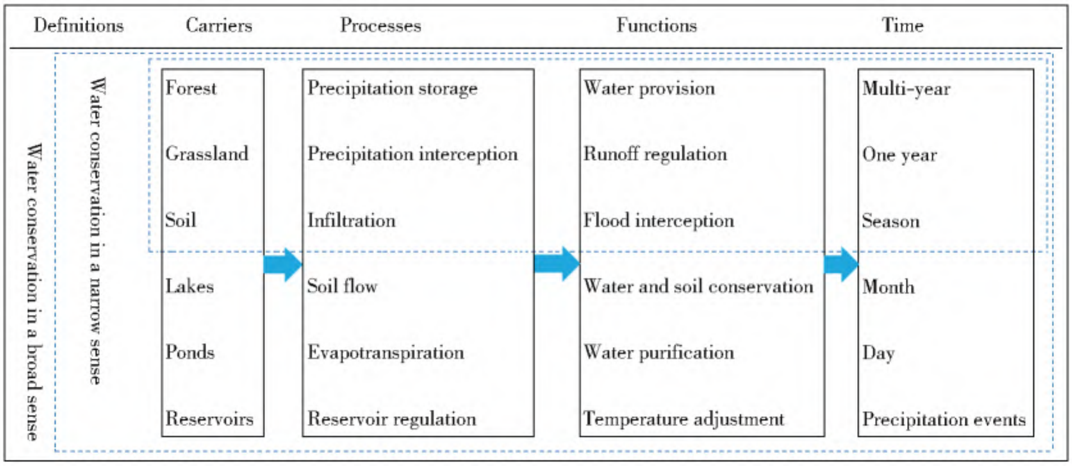

Fig. 3 Definition of water conservation functions

2.2 Water conservation capacity

The water conservation capacity refers to the amount of water stored in an ecosystem in a period of time, and it is often used to assess the water conservation function. Substantially, it refers to the storage capacity of the ecosystem for precipitation in a spatiotemporal range and conditions, i. e., evaporation and soil runoff during non-rainy periods. The time scale (precipitation event, month, and year) shall be considered during the calculation of water conservation capacity. For a precipitation event, the water quantity is calculated by the subtraction of evaporation and runoff produced during the rainy period from the precipitation. For large time scales of month and year, the water quantity refers to the total precipitation minus evaporation and surface runoff during the rainy periods. The water conservation capacity can be divided into potential water conservation capacity and actual water conservation capacity. The former refers to the maximum regulation and storage capacity of an ecosystem for precipitation under sufficient water supply to the ecosystem, and the latter means the actual regulation and storage capacity of the ecosystem for precipitation under actual precipitation and climate conditions. Potential water conservation capacity is the maximum of the actual water conservation capacity. The minimum water conservation capacity is 0, which appears in the case of impervious grounds, where all precipitation is evaporated or becomes surface runoff. The maximum water conservation capacity is the precipitation amount. When the surface vegetation coverage is high enough or the rainwater directly falls into lakes or reservoirs, the rainfall intensity and precipitation amount do not reach the conditions of surface runoff, which makes all precipitation stored in the ecosystem.

3 Quantitative evaluation methods of water conservation based on conceptual models

The evaluation of water conservation means to quantify the amount of water stored in an ecosystem, which is consistent with the connotation of water conservation. Due to the different concepts of water conservation defined by scholars and the differences of study areas, various calculation methods are adopted in practice, mainly including water balance method, precipitation storage method, annual runoff method, underground runoff growth method, canopy interception method, soil water storage capacity method, comprehensive water storage capacity method, and multiple regression method. Each method has advantages, limitations, and applicability scope (Tab. 2).

Tab. 2　Calculation methods of water conservation

No.	Method	Explanation	Formula	Advantages & Disadvantages	Application Scope	Suitable Scales	
						Space	Time
1	Water balance metho	Difference between precipitation and evapotranspiration[43-44]	$W=P-ET$	It is based on the black box theory, with a simple equation and less empirical data required; the accuracy of the results is influenced by the evapotranspiration; in this method, the part of water conservation capacity retained in evaporation is subtracted, and thus calculated values are smaller than actual values.	Areas with low spatial variation	All scales	All scales
		Difference between precipitation and evapotranspiration & other water consumption[45]	$W=P-ET-R$				
2	Precipitation storage method	According to the historical observations of forest evapotranspiration, the proportion of canopy, trunk, and tree evapotranspiration and diffusion in precipitation is determined, and the remainder is the water conservation capacity[46-47]	$W=\beta\times P\times\alpha$	The formula is simple, and the parameters required can be obtained from observations; the surface runoff is ignored, and it is difficult to accurately calculate the proportion of evapotranspiration in precipitation.	Some forest areas with empirical constants	All scales	Month
3	Annual runoff method	The water conservation capacity is assumed to be equal to the annual runoff volume in the forest area, and the annual water consumption is equal for different land cover types. The water conservation capacity is the product of forest coverage rate and annual runoff volume [48]	$W=\alpha\times R$	This method is simple; the difference in evapotranspiration from forest lands and other land types is not considered, and thus the calculation error is large.	Areas with forest cover	Basin scale	Year
5	Underground runoff growth method	Forests can convert surface runoff into groundwater runoff, so that the groundwater runoff is more in forest areas than in non-forest areas. The water conservation capacity is the increase in groundwater runoff in forest areas as compared to non-forest areas [49-50]	There is no uniform formula for the time being	The parameters required are few and can be obtained from field observations; the water-holding capacity of the above-ground parts of forest lands is neglected and the calculated values are smaller than actual values.	Areas with forest lands	All scales	Month, year

Tab. 2 (Continued)

6	Canopy intercept-ion method	The water conservation capacity is the amount of water that falls to the ground without being retained by the forest canopy and is calculated according to the precipitation amount and canopy interception rate [28]	$W=(1-\varphi)\times P$	The calculation is simple and feasible since few parameters are involved; however, surface runoff and evapotranspiration are not considered, which makes the calculation results slightly larger than the actual values.	Areas with a high forest coverage rate	All scales	All scales
7	Soil water storage capacity method	The water conserved is retained in soil; the water conservation capacity is the short-term retention amount of precipitation by the non-capillary porosity of the soil, which can be calculated by the multiplication of the soil thickness and the non-capillary porosity [10,20,51]	$W=10^4\times\lambda\times h$	This method is simple and easy to operate; however, only the water stored in the soil is calculated, with the water stored in other layers and the water consumed by the forest ignored.	Areas with forest cover	All scales	All scales
8	Comprehen-sive water storage capacity method	The water conservation capacity is the sum of canopy interception, water-holding capacity of litter, and soil water storage capacity [37-38,52]	$W=I+K+Q$	The water conservation capacities of canopy layer, litter layer, and soil layer are calculated respectively, which facilitates the comparison of conservation capacities of different action layers; many measured values are required, and forest evapotranspiration is ignored, with the calculation result being the theoretical maximum.	Areas with abundant precipitation	Small basin scale	All scales
9	Multiple regression method	A multiple linear regression model for calculating water conservation capacity is obtained according to characteristics of underlying surface and meteorological factors [53]	No uniform formula available	It fully considers the influence factors of water conservation and is logical; however, the modeling requires a large number of measured data, and it is difficult to promote the model.	Areas where regression model parameters are obtained	Basin scale	Month, year

Note: W is the water conservation capacity, mm; P is the precipitation, mm; ET is the actual evapotranspiration, mm; R is the surface runoff, mm; I is the canopy interception capacity, mm; K is the water-holding capacity of litter layer, mm; Q is the water storage capacity of soil layer, mm; β is the proportion of precipitation storage by forest in precipitation, %; α is the forest coverage rate, %; φ is the canopy interception rate, %; λ is the non-capillary porosity of soil, %; h is the soil thickness, cm.

Most of the above methods calculate the water conservation capacity from one dimension, and the water conservation capacity characterized by different methods varies. For example, the soil water storage capacity method regards the amount of water stored in soils as water conservation capacity, while the comprehensive water storage capacity method considers the sum of canopy interception capacity, water-holding capacity of litter, and soil water storage capacity as the water conservation capacity. Thus, the results obtained by different methods are less comparable. The comprehensive water storage capacity method takes into account the amounts of water retained in different action layers, which is close to the connotation of water conservation, and this method has a relatively wide application range [37-39], as it can compare the contributions of different action layers to the total water conservation capacity. The water balance method views the amount difference between the water received and the water consumed in a period of time in an area as water conservation capacity, which best matches with the connotation of water conservation. In addition, it is applicable to a wide spatiotemporal scale and thus is currently the most widely used method [29,40-41]. Nie et al. [42] considered surface runoff as water conservation capacity and estimated the water conservation capacity of the Qinghai-Tibet Plateau with the water balance method. The results showed that the multi-year (1982-2003) average water conservation capacity was $3.451\,29 \times 10^{11}$ m^3, with a high water conservation capacity in the southeast and a quite weak water conservation capacity in the northwest. Gong et al. [4] considered the result of subtracting surface runoff and evapotranspiration from precipitation as water conservation capacity and estimated the water conservation capacity of the national ecosystem with the water balance method. The results showed that the total water conservation capacity was 1 222 433 million m^3 in 2010, with a spatial trend of being high in the southeast and low in the northwest, decreasing from east to west.

Water conservation is the result of the synthetic action of ecosystems and hydrological processes, which is related to various factors such as ecosystem type, climatic conditions, underlying surface properties, and human activities and is a complex and comprehensive concept [41-42]. How to accurately calculate the water conservation capacity on multiple spatiotemporal scales is still a difficult and important topic of study at present. According to the connotation of water conservation defined in this paper, the water conservation capacity of surface ecosystems (including lakes and reservoirs) is precipitation falling to the ground minus the evaporation and surface runoff during the rainy period. It is recommended to use a hydrological model with a physical mechanism to calculate water conservation capacity. The actual evapotranspiration (ET_1) and surface runoff (R_s) during the rainy period are simulated with the hydrological model. The water conservation capacity is $W = P - R_s - ET_1$. The evapotranspiration, interflow, and soil water content during the non-rainy period are all part of the water conservation capacity. It is recommended to use a distributed hydrological model on a daily scale to calculate water conservation capacity. In a complete flood or on a long time scale such as a month or a year, the water conservation capacity of the rainy period is calculated directly with the model and summed to be the total water conservation capacity over the calculation period.

4 Quantitative evaluation methods of water conservation based on dynamic models

With the deepening of understanding regarding water conservation, many comprehensive evaluation models for water conservation have been developed on the theoretical basis of the hydrological cycle and with the help of GIS, RS, and computer technology. The water conservation evaluation has gradually developed from the above traditional calculation methods to the comprehensive evaluation methods based on dynamic models (Tab. 3). These models can realize the dynamic simulation analysis on water conservation and have become the main way to quantitatively evaluate water conservation. Models can be divided into two main categories: the traditional hydrological models represented by the SWAT model, and the emerging ecosystem service evaluation models represented by the InVEST model [54]. The hydrological models focus on the drivers of water conservation and are more concerned with the simulation of water conservation processes; the emerging ecosystem service evaluation models focus on the final ecosystem services and the visual representation of the evaluation results on the landscape scale.

4.1 InVEST model

The InVEST tool was jointly developed by Stanford University, the World Wide Fund for Nature, and The Nature Conservancy. It is an effective tool to evaluate ecosystem services and is able to express ecosystem services in a quantified, valued, and visualized way and predict ecosystem services under future scenarios. Nelson et al. [55] applied the InVEST model to the Willamette River basin in the United States and simulated and predicted changes in ecosystem services (water quality, soil conservation, and carbon storage), biodiversity conservation, and commodity production levels under different land use/

coverage scenarios to provide a basis for decision making in the management and exploitation of local natural resources. Since then, many scholars have used the InVEST model to assess a variety of ecosystem services in different regions [62-64] and explored the sensitivity and applicability of the model. The results showed that the model produced good simulation effects in different regions [65-66].

Tab. 3 Evaluation models of water conservation

Model	Formulas	Scale		Advantages & Disadvantages
		Time	Space	
InVEST[45,55]	$R=\min\left(1,\frac{249}{V}\right)\cdot\min\left(1,\frac{0.9\times I_T}{3}\right)\cdot\min\left(1,\frac{K_{sat}}{300}\right)\cdot Y$ $Y=\left(1-\frac{ET_a}{P}\right)\cdot P$	Year	30 m-10 km grid cells; basin	Visualization and dynamics are strong; however, it requires many input data, and only annual average water conservation capacity can be simulated.
SWAT[56-57]	$Q_1=\sum_{i=1}^{n}(P_i-ET_i-Q_{ij})A_i$	Day, month, and year	Hydrological response cells; basin	It has a strong physical mechanism, accurate simulation of hydrological processes, and time resolution of daily time step; however, the uncertainty of model parameters is large, and the correction is difficult.
Cellular automata model [58]	$Q_2=\sum_{i=1}^{m}W_{(t+1)i}+D_{(t+1)}\bar{E}\cdot n_1\cdot\Delta t$	Precipitation event	Hydrological response cells; cellular elements	It provides a scale-up approach; the model is only applicable to the precipitation season (July-August).
SEBS and SCS model [41,59]	$R=P-ET-Q$ $E_{daily}=8.64\times10^7\overset{24}{\underset{0}{\Lambda}}\times\frac{R_n}{\lambda\rho_w}$ $Q=\frac{(P-0.2S)^2}{P+0.8S}, P\geqslant0.2S$	Year	Region	Evapotranspiration and surface runoff are accurately calculated; lost groundwater runoff is not considered and the results are larger than the actual values.
Terrain Lab[60-61]	No uniform formula available	Day	Grid cells; basin	It considers the variability of the vegetation-soil system in vertical direction, and the calculation of hydrological parameters is accurate; the water balance verification is required for practical application.

Note: R is the water conservation capacity, mm; V is the flow rate coefficient; I_T is the topographic index (dimensionless); K_{sat} is the saturated hydraulic conductivity of soil, cm/d; Y is the water yield, mm; ET_a is the actual evapotranspiration, mm; P is the precipitation, mm; Q_1 is the total water conservation capacity, m^3; ET is the evapotranspiration, mm; Q is to the surface runoff, mm; A is the area of hydrologic response unit HRU, km^2; i is the ith hydrologic response unit; n is the total number of hydrologic response unit; j is the value corresponding to different time scales (year, month, and day); Q_2 is the total amount of water retained by forests at the time $(t+1)$, mm; $\bar{E}$ is the average evaporation rate of the saturated canopy, mm; $W_{(t+1)}$ is the amount of water retained by reservoirs of a cellular element at the time $(t+1)$, mm; $D_{(t+1)}$ is the leakage to the deep soil at the time (t+1), mm; m is the total number of cellular elements in the simulated area; n_1 is the number of simulations; Δt is the time step; E_{daily} is the actual daily evapotranspiration, mm; $\overset{24}{\underset{0}{\Lambda}}$ is the daily evapotranspiration ratio (dimensionless); ρ_w is the density of water, kg/cm^3; R_n is the net surface radiation flux, W/m^2; S is the possible retention in the basin at that time, mm.

The InVEST model consists of numerous modules. The water yield module is an important component of water-related ecological service assessment and is commonly used to calculate the water conservation capacity of ecosystems [67], which can reflect the spatial differences in water conservation function on regional scales. It has been applied in some places such as the United States, West Africa, and China (e. g., the Loess Plateau, Sanjiangyuan region, and mountainous areas in Beijing) and has achieved good simulation results [30,68-72]. The water yield module uses water balance as the basic principle to calculate the actual evapotranspiration by the Budyko theory [73]. On this basis, the water yield of the grid cell is calculated, which is defined as the precipitation minus the actual evapotranspiration. Then the water yield is further corrected according to the surface characteristics to give the final water conservation capacity, with the main calculation equations shown in Tab. 3.

The InVEST model is the most widely used water conservation evaluation model, which has unique advantages and some limitations. The main advantages are as follows: The spatial distribution characteristics of water conservation capacity are presented in the form of a map, which helps to analyze the spatial differences of water conservation function in the region and identify important water conservation areas; the InVEST model can evaluate water conservation, soil conservation, carbon storage, and other ecosystem services and provide a basis for decision making on ecological conservation and resource management depending on the comprehensive evaluation and tradeoff of multiple ecosystem services [74]; the model is highly dynamic and can predict water conservation capacity under different land use/coverage scenarios and climate scenarios [75]. The main limitations are as follows: The dynamic interaction between surface runoff and soil water is ignored in the calculation of water yield, and the calculation results have errors; the time scale is a year, which makes the model unable to reflect the variation characteristics of water conservation capacity within the year and in the flood/dry seasons; the water yield module needs the input of many raster data and biophysical parameters, which is sensitive to the input data, and thus the accuracy of the results is greatly affected by the input data [76].

4.2 SWAT Model

The SWAT model is a distributed hydrological model developed by the Agricultural Research Service, United States Department of Agriculture to analyze and predict long-term changes in hydrological processes in complex basins. With a strong physical mechanism, this model can accurately simulate and analyze the spatiotemporal variations of hydrological processes such as evapotranspiration, runoff, soil water, and base flow [56]. It has been widely used in Canada, cold regions of North America, and the Heihe region and Sanjiangyuan region in China, with good simulation results achieved [77-79].

In the SWAT model, the basin is first divided into sub-basins, and then the sub-basins are divided into hydrologic response units (HRUs) according to the surface characteristics [80]. A HRU is used as the minimum unit for the simulation of evapotranspiration, surface runoff, groundwater, and soil water processes [76]. The water conservation capacity is defined as the result of subtracting evapotranspiration and other water consumption from precipitation.

The SWAT model can calculate the water conservation capacity of spatially discontinuously distributed landscapes [57] and reveal the differences in water conservation capacity among different vegetation types. In addition, the model can analyze the water conservation capacity at different time scales: the short-term flood variation can be analyzed on the daily scale; the runoff variation within a year can be studied and the runoff regulation function can be analyzed on a monthly scale; the water supply capacity can be investigated on the yearly scale. However, it is difficult to correct the model, and the results are highly affected by parameters.

4.3 Other models

In addition to the above-mentioned InVEST model and SWAT model, scholars have proposed some calculation models based on their understanding of the connotation of water conservation. For example, Wang et al. [58] proposed a new modeling method for forest water conservation capacity based on cellular automata, which can calculate the water conservation capacity of forest ecosystems on different spatiotemporal scales, providing a calculation method that extrapolates from small to large scales. However, due to the complexity of the computation, it has not been promoted for application yet. Nie [41] and Zhang [59] combined the SEBS evapotranspiration model and the SCS runoff estimation model to calculate water conservation capacity. Although the evapotranspiration and surface runoff were calculated accurately, the final calculated water conservation capacity was larger than the actual value since the groundwater runoff was not considered.

Some distributed hydrological models are also used to calculate water conservation capacity. These hydrological models mostly focus on the simulation of hydrological cycles, such as evapotranspiration, surface runoff, and soil water, and on this basis, the water conservation capacity of the basin is obtained in light of the water balance principle, such as the Terrain Lab model. The Terrain Lab model was developed on the basis of the distributed hydrology-vegetation model proposed by Wigmosta[81], which simulates hydrological processes with pixel as the unit and can calculate actual evapotranspiration, soil water content, soil moisture, and other hydrological process parameters [60-61]. The Terrain Lab model fully takes into account the characteristics of the vegetation-soil system in the vertical direction and can accurately simulate hydrological process parameters, which is suitable for the calculation of the water conservation capacity of forest ecosystems. However, the model does not provide the validation of water balance within the basin and thus the water balance needs to be verified in practical applications.

5 Value assessment on water conservation

As an important service function of ecosystems, water conservation provides numerous ecological benefits and is an important assessment element of ecosystem services. The value assessment on water conservation is to express the water conservation capacity of ecosystems from the perspective of monetary value. It is often used in trade-off analysis between different ecosystem services, accounting of the total value of ecosystem services, and ecological compensation. On the basis of calculating the substance quantity of water conservation, various methods are generally used to convert the water conserved by ecosystems into value, and the value magnitude is used to evaluate the water conservation function [82-84]. Currently, alternative approaches are mostly used to indirectly calculate water conservation value, and the alternative engineering method is most widely used. In addition, Jiang proposed a fuzzy mathematical model for calculating the value of forest water conservation from the perspective of the factors that constitute the value of water resources [85].

5.1 Alternative engineering method

The alternative engineering method is based on the principle that an ecosystem is considered as a natural reservoir. Assuming that there exists engineering (e.g., artificial reservoir) with the same water conservation capacity as the ecosystem, the construction cost or value of such engineering can be used to replace the water conservation value of the ecosystem. The construction cost or value of such engineering is considered as a shadow price and the total substance quantity of water conservation is multiplied by the shadow price to yield the water conservation value[1,86-87], as shown in Equation (1).

$$V = W \times P_0 \tag{1}$$

where: V is the water conservation value, CNY; W is the total water conservation capacity, m^3, which is the product of the water conservation capacity above and the size of the study area; P_0 is the shadow price, $\mathrm{CNY/m^3}$.

The calculation of water conservation value with the alternative engineering method relies on the accurate calculation of substance quantity of water conservation and the selection of a suitable shadow price. There are many methods to calculate the substance quantity of water conservation, which have been discussed above. The shadow prices are not selected in a uniform way, and the followings are the main options [88]: the construction cost of the reservoir engineering, usually the cost per unit reservoir capacity; the commodity price of water supply; the cost of electricity production; the differential land rent; the cross-regional freight of water resources; the desalination cost. Among them, the first two are most widely used in practical applications.

In early studies, researchers often selected a cost per unit reservoir capacity of 0.67 $\mathrm{CNY/m^3}$ as the shadow price when calculating the water conservation value with the alternative engineering method. For example, Ouyang et al. [1] used the water balance method and alternative engineering method to analyze the economic value of water conservation in terrestrial ecosystems in China, and the results showed that the water conservation value was 2.71×10^{11} CNY/a. Deng et al. [28] used the canopy interception method and alternative engineering method to assess the water conservation function of forest ecosystem in the upper reaches of Yangtze River and calculated the annual economic value of water conservation to be $1\,606.179 \times 10^{8}$ CNY. This indicates that the local forest has great water conservation benefits. Liu et al. [51] studied the water conservation capacity of the ecosystem in the Sanjiangyuan region from the perspective of water storage capacities of litter and soil layers and used the alternative engineering method to calculate the water conservation value. The results showed that the total value of water conservation in the Sanjiangyuan region was $1.103\,4 \times 10^{10}$ CNY.

With the development of society and economy, it is not practical to still select the cost per unit reservoir capacity of 0.67 CNY/m^3 as the shadow price. In recent years, researchers have selected a more reasonable shadow price, taking into account the current economic development. For example, Lai et al [40] used the InVEST model and the alternative engineering method to calculate the water conservation value when evaluating the water conservation function in the Sanjiangyuan region. They selected the cost per unit reservoir capacity of 7.02 CNY/m^3 as the shadow price and calculated that the water conservation value in the Sanjiangyuan region was 1.07×10^{11} CNY in 2008. Liu et al. [89] used the InVEST model and the alternative engineering method to evaluate the water conservation capacity of the ecosystem in the upper reaches of the Minjiang River. They selected the water supply price of 0.83 CNY/m^3 as the shadow price. The results showed that the total water conservation capacity in the upper reaches of the Minjiang River was 4.919 billion m^3 in 2010, and the water conservation value is 4.083 billion CNY.

As an effective method for estimating the water conservation value, the alternative engineering method is highly operable in practical application due to its complete theoretical basis and is widely used in the assessment on water conservation value in China. However, there are numerous methods for selecting shadow prices, and the different selection criteria may result in big differences in the calculation results of the same study area, leading to poor comparability of results. In addition, when determining the shadow price, one should consider the current reservoir construction cost and water resources price in conjunction with the current socio-economic development to select a more practical shadow price.

5.2 Fuzzy mathematical model for forest water conservation value

In addition to the above-mentioned alternative engineering method that has been widely used, Jiang[3] proposed a fuzzy mathematical model to calculate the forest water conservation value [Equations (2) and (3)]. The model views the forest water conservation value system as a complex fuzzy system and fully considers three types of factors that constitute the water conservation value: natural factors, social factors, and economic factors, which can accurately calculate the economic value of forest water conservation theoretically. However, it is difficult to operate in practical applications since there are many factors to be considered in the model. Thus, it is rarely used at present and needs further development.

$$V = (A \times \boldsymbol{R}) \times \boldsymbol{S} \tag{2}$$

$$\boldsymbol{S} = (P, P_1, P_2, P_3, 0) \tag{3}$$

where: V is the forest water conservation value; A is the weight value of factor evaluation; $\boldsymbol{R}$ is the comprehensive evaluation matrix consisting of the evaluation matrices of single factors affecting forest water conservation; $\boldsymbol{S}$ is the price vector of water resources.

6 Conclusion and prospects

Depending on the analysis of the research results of water conservation, the main conclusions of this paper are drawn as follows:

(1) The research history of water conservation can be divided into four stages: cognition and germination stage (1800-1950), mainly based on observational data to analyze the relationship between forests and water and with water conservation regarded as the influence of forests on river flow; theory development stage (1960-1970), with a deeper understanding regarding the processes of canopy interception, water retention of litter, and soil water storage; quantitative calculation stage (1980-2000), with a clearer concept of water conservation and unprecedented development in water conservation estimation methods; comprehensive model evaluation stage (recent ten years or so), mainly using comprehensive models to evaluate the water conservation function within a region.

(2) Water conservation refers to the process and ability of an ecosystem to fully maintain water in the system through the interception, infiltration, and storage of precipitation in vegetation layer, litter layer, soil layer, lake, and reservoir in a spatiotemporal range. It not only meets the demand for water resources in the system but also provides water resources to the external areas and middle and lower reaches of the system.

(3) The functions of water conservation, a dynamically evolving concept, have a rich and expanding connotation that can be distinguished in a narrow and broad sense. In a narrow sense, the functions of water conservation refer to the interaction of the ecosystems formed by forests, grasslands, and soils with the water in the process of water conservation, including flood storage, runoff regulation, and water supply. In a broad sense, the functions of water conservation include the combined influence and ecological benefits of hydrological processes on local climate, water, and soil. Not only the ecosystems formed by forests, grasslands, and soils are considered, but also the water conservation by lakes, reservoirs, and ponds is involved. The functions include water purification, soil and water conservation, and local temperature regulation in addition to water supply, runoff regulation, and flood storage.

(4) Water conservation evaluation can be carried out in terms of both substance quantity and value, and there are many relevant calculation methods and evaluation models. Each method has advantages, disadvantages, spatiotemporal scale, and application scope. In practical application, the evaluation method needs to be selected flexibly.

There are several shortcomings in the existing studies as follows:

(1) The connotation of water conservation is not uniform. Different researchers give their connotation of water conservation, and then provide the calculation equations of water conservation capacity according to the connotation. As a result, the calculated results may significantly vary even in the same time and area.

(2) The objects of water conservation capacity calculation are not inclusive. The existing calculation only considers the water conservation capacities of vegetation and soil and ignores the contributions of lakes, reservoirs, and ponds to water conservation. In the Qinghai-Tibet Plateau, the uncertainty is great in the calculation of water conservation capacity for the areas where there are a large number of inland lakes.

(3) The hydrological cycle is too simplified in the water conservation capacity calculation. The water conservation capacity calculation is mostly done on a yearly or monthly scale for simplicity, and the water balance is not considered enough, which results in great uncertainty in the calculation of each hydrological element. In general, water conservation is the result of subtracting evaporation and runoff from precipitation. Since the evaporation and interflow during non-rainy periods should be part of water conservation, simply repeated calculations likely lead to negative values, which are unreasonable.

In view of the above shortcomings, the core development direction of water conservation research and application is "unifying standards, improving objects, strengthening the hydrological cycle, coupling multiple models, and realizing accurate water conservation calculation". The further in-depth study can be carried out in the following five aspects:

(1) Unifying the concept and connotation of water conservation. It is necessary to deepen the connotation of water conservation, propose a reasonable definition of water conservation, unify the evaluation indexes as per the definition, and standardize the evaluation of water conservation functions according to the research on the development and mechanism of water conservation.

(2) Improving the study objects of water conservation. The research on water conservation should consider not only the vegetation and soil but also the water storage function of permafrost, lakes, ponds, and reservoirs. Thus, during the calculation of water conservation, the vegetation, soil, permafrost, lakes, ponds, reservoirs, and rivers in the study area should be taken as the study objects for comprehensive consideration with the aim of reducing the uncertainty of water conservation calculation.

(3) Strengthening the hydrological cycle calculation and realizing the coupling of multiple models. The latest distributed hydrological models are used to accurately calculate the hydrological cycles in the study area (or basin) and provide accurate hydrological elements for obtaining more accurate water conservation capacity. By the coupling of the ecological model, hydrological model, lake model, and permafrost model, water conservation can be studied more comprehensively. This makes up for the shortcomings of single models and facilitates the understanding of water conservation from a more systematic view.

(4) Forecasting the water conservation under climate change and land use change scenarios. Previous studies have shown that climate change and land use change are important factors influencing water conservation function. Reasonable prediction of water conservation function can help comprehensive management and decision-making on water resources, cope with future changes, and prevent risks.

(5) Enhancing the regional correlation research. The current studies mainly focus on the water conservation function within a single basin, but rarely consider the influence of changes in the upstream water conservation area on the midstream and downstream ecosystems, water quantity, and human activities. Therefore, enhancing regional correlation research can better give play to water conservation.

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