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Integration of Remote Sensing Observations and Models Supports the Regional Sustainable Development in Heihe River Basin, China

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Integration of Remote Sensing Observations and Models Supports the Regional Sustainable Development in Heihe River Basin, China

Abstract

The Heihe River Basin is the second largest inland river basin in China. During the last few decades, this region has been faced with a serious of severe ecological and environmental problems caused by rapid economic growth and climate change. Two decades ago, with the increase of population and water consumption in the upper and middle reaches, the ecological water consumption in the lower reaches was greatly squeezed, which eventually led to serious ecological disasters, such as the shrinkage of the natural oasis, the drying up of the lakes, and frequent sandstorms in the lower reaches. The sustainable development of the region has been seriously challenged. To accurately monitor changes in hydrological and meteorological variables at watershed scale and support the wise use of water resources in this region, the Heihe Remote Sensing Experimental Research Station (HRSERS) was founded in 2009. The foundation of HRSERS has greatly improved the level of scientific research and decision support in the Heihe River Basin. The main achievements include: (1) the first watershed scale (with an area of 143000 km^2) integrated observation system in China is constructed, and a large number of long-term observation data are obtained. More than 200 papers have been published using the observed dataset; (2) key eco-environmental variables in Heihe River Basin are retrieved from remote sensing data; (3) the theoretical framework and method system for the authenticity inspection of heterogeneous surface remote sensing products have been established, and some related national standards have been approved; (4) the eco-hydrological model is improved by adding glacier, snow and permafrost modular, and the eco-hydrology-economic coupling model is developed for the whole Heihe River Basin to full couple the natural processes and social processes; (5) the United Nations Sustainable Development Goals (SDGs) were monitored at the basin scale and regional scale, and provides scientific support for the sustainable development and decision-making of Heihe River Basin.

Keywords

Heihe River Basin; remote sensing; integrated observation; validation; model integration; eco-hydrology; decision support; sustainable development

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遥感综合观测与模型集成研究为黑河流域生态环境保护与可持续发展提供科技支撑

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摘要 中国科学院黑河遥感试验研究站（以下简称“黑河遥感站”）立足寒旱区内陆河流域，通过星空地一体化的综合观测手段，精细化地观测黑河流域的水文气象要素，在科学上为寒旱区定量遥感、尺度转换、模型集成等方面的研究作出突出贡献，在服务国家需求上为流域可持续发展、生态环境保护、国家公园建设等提供科技支撑。黑河遥感站构建了我国第一个多要素-多尺度-精细化流域综合观测系统，积累了大量的长期观测数据，为流域综合观测提供了示范；开展了深入的寒旱区定量遥感研究，形成了一系列寒旱区关键特色遥感数据产品，且得到了广泛应用；构建了异质性地表遥感产品真实性检验的理论框架和方法体系，并形成了相关国家标准；在黑河流域生态-水文-社会经济模型，以及流域可持续发展决策支持系统的发展中起到关键支撑作用。总体上，黑河遥感站实现了从传统单站观测向流域综合观测系统的转型，实践和推进了观测-模型-决策一体化研究，是新时代山水林田湖草系统综合监测的典型，也是以流域为单元开展地球表层系统科学研究的示范。

关键词 黑河流域，遥感，综合观测，真实性检验，模型集成，生态水文，决策支持，可持续发展

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黑河流域是我国第二大内陆河流域，面积约 14.3 万平方公里。在黑河流域从上游至下游，形成了以水为纽带的多元自然景观，包括冰川、积雪、冻土、草原、森林、河流/湖泊、绿洲、戈壁、沙漠等[1,2]。黑河流域寒区旱区并存，上游属于极端寒冷环境，而下游属于极端干旱环境。黑河流域历史悠久，早在汉朝时期这里已经有大规模的农田水利设施[3]。多元的自然景观与复杂的人文过程交织在一起，使得黑河流域成为开展星机地综合遥感观测与模型集成的理想天然地球科学实验室。

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近年来，随着气候变化与经济发展，黑河流域出现了一系列的生态环境问题。例如：黑河流域上游冰雪、冻土快速退化，过度放牧和矿产开发对上游高寒生态系统造成了严重的影响和破坏；中下游农业灌溉与生态用水矛盾突出，曾经一度随着上中游人口增加与耗水增多，大幅挤占下游生态用水，最终导致下游天然绿洲大面积萎缩、居延海干涸、沙尘暴频发等严重的生态灾难。虽然通过行政手段制定了中、下游分水方案，使得下游的生态得到了一定的恢复[4]，但是黑河流域仍然面临着严重的生态环境问题，威胁着该区域的可持续发展。当前急需流域尺度的立体化网络化的综合观测与模型集成研究来科学评估和指导黑河流域的可持续发展，并为寒旱区内陆河流域科学管理提供支撑。

中国科学院黑河遥感试验研究站（以下简称“黑河遥感站”）围绕黑河流域生态环境保护与流域可持续发展，致力于生态水文要素综合监测与模型集成研究，建立了涵盖上、中、下游的流域尺度水文气象综合观测体系，发展和生产了一批寒旱区遥感数据产品，改进和开发了一系列针对寒旱区过程的生态、水文模型，支撑了黑河流域水资源管理与优化、生态保护与修复等相关政策制定。

1 构建了黑河流域生态水文观测综合观测系统

流域观测系统是流域科学研究中的新手段，兼顾流域中水文、生态、气象等观测的时空尺度，地面观测与遥感观测相配合，从流域整体的角度出发考虑观测的代表性，将监测与控制试验并重，重视新兴观测手段与信息系统和模型的高度集成[5]。黑河遥感站在黑河流域初步建成了流域观测系统。从区域代表性上，该系统包含了黑河上游的高寒生态系统、中游的人工绿洲与荒漠生态系统和下游的天然绿洲生态系统；从观测要素上，包含植被（如碳通量、树干液流、叶面积、物候期、生物量、太阳诱导叶绿素荧光）、大气（如温度廓线、湿度廓线、辐射、降水、潜热通量、感热通量等）、土壤（如温度廓线、湿度廓线、热通量）等；从观测手段上，将单点观测与网络化观测相结合，可以获取米级到千米级不同遥感尺度上的代表性观测。

针对我国生态系统监测设备严重依赖进口、观测设备自动化和信息化程度低，以及与遥感和模型尺度不匹配等瓶颈问题，通过原始和集成创新，研发了国产自动化、智能化新型生态系统关键参量监测设备，并研制了生态监测物联网关键设备（如通用型数据记录传输仪、低功耗长距离无线组网中继和终端设备）和生态监测物联网信息系统（图 1）。

黑河流域生态水文观测系统构建了我国第一个多要素-多尺度-精细化流域综合观测系统，包括水文气

图 1　黑河遥感站研发的无人机物联网中继系统采集无网络覆盖观测站点数据示范

象观测（加强观测期有23个观测站，目前长期运行站点为11个）、生态水文传感器网络及卫星遥感，引领了我国流域系统综合观测研究（图2）。流域内长期运行11个气象观测站、11个涡动相关仪（EC）、2套双波段水热观测大孔径闪烁仪（OMS）、3套大孔径闪烁仪、1套积雪观测系统。该综合观测系统覆盖黑河流域上、中、下游区域，涵盖草地/草甸、农田、湿地、柽柳林、胡杨林、荒漠、戈壁等主要地表类型，观测时间序列最长的站点已有13年的数据积累[6-8]。

2 深入开展定量遥感反演及遥感产品真实性检验研究

基于电磁波辐射传输模型，黑河遥感站在大量地基遥感与星机地同步观测试验的基础上，发展了面向寒旱区陆地关键参量的定量遥感算法。包括：积雪、

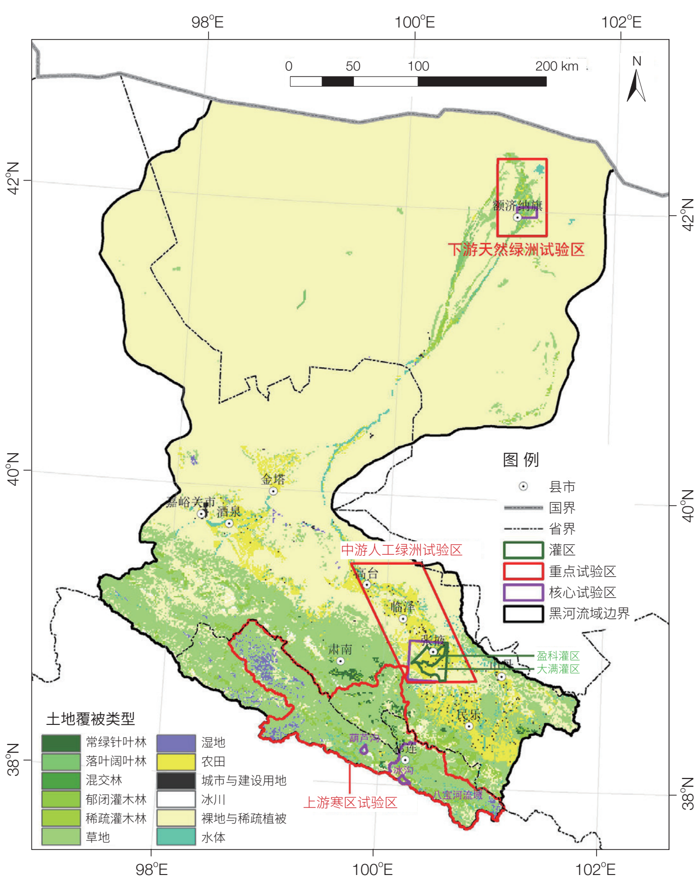

图2　黑河上游高寒山区试验区、中游人工绿洲试验区和下游天然绿洲试验区空间分布图

冻土、冰川、河湖冰等陆地冰冻圈要素，以及植被、碳循环、水循环和能量循环等干旱区地表关键参量。在对长时间序列遥感观测数据的基础上，黑河遥感站研发了面向冰冻圈与寒旱区关键参量的遥感产品。其中，我国逐日长时间序列雪深遥感数据产品、地表冻融遥感产品等，被国内外学者认可并广泛应用在气候变化、水文水资源和灾害等领域[9-12]。

真实性检验是评价遥感产品质量、可靠性和适用性的唯一手段，也是提高遥感产品精度的主要依据。遥感产品真实性检验要依靠大量的地面观测来遥感象元尺度的地表真值。这也是黑河遥感站的主要目标之一。在黑河上、中、下游试验区设计了多尺度嵌套的土壤水分和地表温度观测网络，来应对从米级到千米级不同分辨率遥感数据的真实性检验。经过多年努力，黑河遥感站构建了异质性地表遥感产品真实性检验的理论框架和方法体系（图3），系统地发展了异质性地表优化采样、多尺度观测、尺度上推、空间代表性误差估计的新理论、新方法，解决了异质性地表遥感产品真实性检验的难题；并制定了多项遥感产品真实性检验国家标准[13]。

3 研发了流域“水-土-气-生-人”复杂过程的综合集成模型

3.1 开发冰川-冻土-积雪过程高寒山区水文模型

黑河上游高寒山区山径流的预测精度直接影响中下游水资源分配，传统的分布式水文模型多针对温带地区设计，直接用于积雪、冰川、冻土广泛分布的寒区时，模型机理会失效，模拟能力和应用效果也明显变差。因此，鉴于寒区水文过程的特点，开发适合该区域特征的寒区生态水文模型对黑河流域水资源管理具有重要意义。

黑河遥感站利用黑河上游分布式的气象水文观测系统、积雪和冻土观测系统、径流观测等长期观测数据，在分布式水文模型（GBHM）中增加积雪、冰

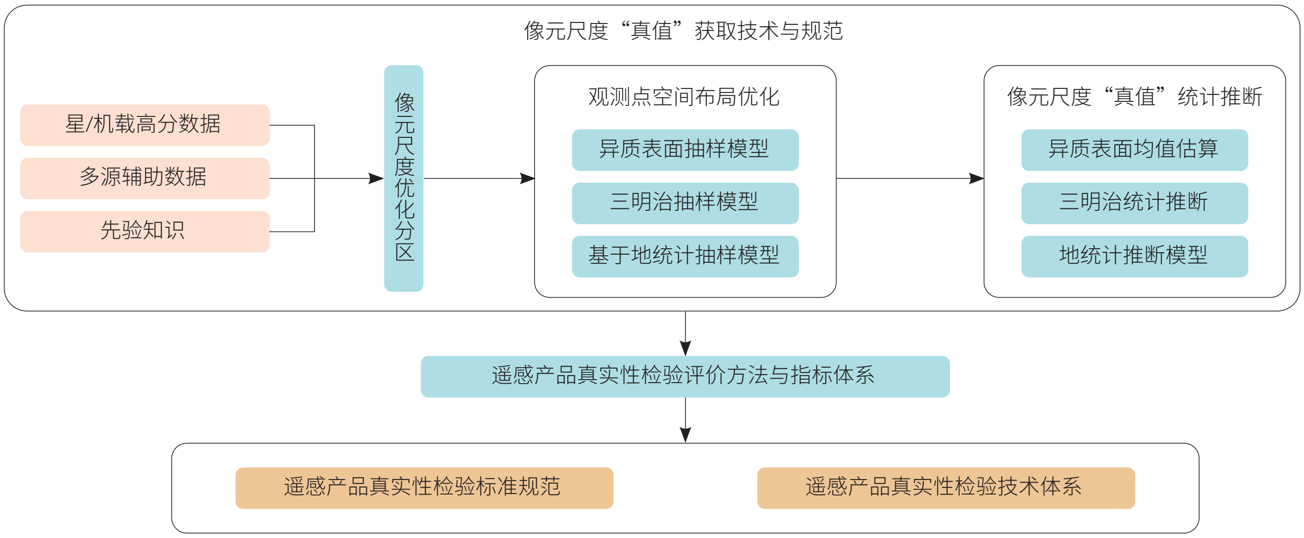

图 3　黑河遥感站构建的遥感产品真实性检验方法体系

川和冻土模块。积雪过程综合了多套积雪模型方案，构建了关键的积雪能量平衡方程，发展了基于能量平衡方程的多层积雪模块[14]。考虑到黑河上游面积小于 1 平方公里的冰川占绝对优势，冰川模块采用了计算过程相对简单且对冰川规模无严格限制的高阶冰流模型。冻融过程是在 GBHM 的框架内，耦合了具有较强物理意义且能细致描述寒区冻土水热过程的 SHAW（Simultaneous Heat and Water Model）模型[15]。考虑了积雪、冰川、冻土要素后分布式水文模型对黑河上游径流模拟精度显著提高（图 4）。

3.2 研制耦合生态-水文-经济的集成模型

黑河流域综合观测系统获取的观测数据，为构建耦合生态-水文-经济的全流域生态水文集成模型提供了数据基础，保障了集成模型的顺利完成；集成模型整体框架如图 5 所示。在该框架下，模拟分析了历史时期（1981—2010 年）黑河上游的生态水文现状及空间分布格局，并结合气候变化情景（RCP① 4.5）开展了长时间序列的预估。考虑上游来水变化，模拟了2001—2060 年期间黑河中下游的生态水文过程变化。首次利用模型和观测手段闭合了黑河流域水量平衡。模拟了黑河流域不同空间尺度（如上、中、下游，以及灌区、河道、

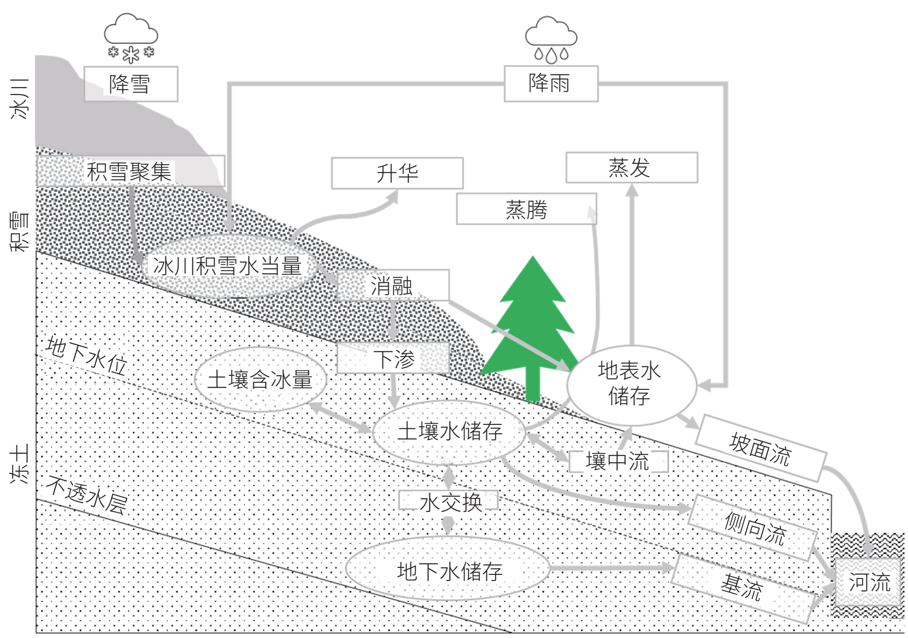

图 4　黑河上游寒区水文模型的整体框架

① 典型浓度路径。

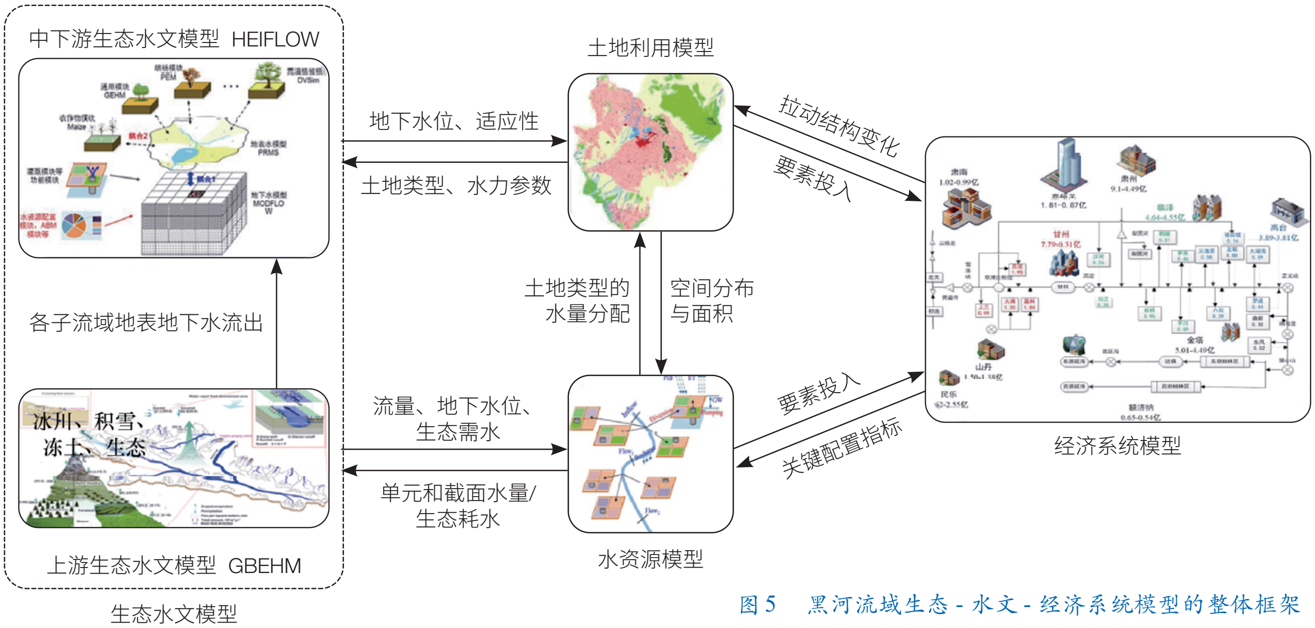

图 5 黑河流域生态 - 水文 - 经济系统模型的整体框架

景观等）的水量平衡，定量化了水循环过程各个分量的贡献[16]。预测了黑河流域社会经济发展路径，结合联合国政府间气候变化专门委员会（IPCC）2010 年提出的共享社会经济路径，综合考虑人口、经济、技术进步、水资源利用等因素，形成黑河流域的共享社会经济路径（SSPs）不同发展路径，并定量评价了不同 SSPs 路径下水压力、社会经济等要素的响应的关系。

4 建立了黑河流域可持续发展决策支持系统

在联合国可持续发展目标（SDGs）和 IPCC SSPs 研究框架下，结合黑河流域自然特征和关键流域发展问题，将 SDGs 和 SSPs 降尺度到流域尺度，建立了流域可持续发展目标（RiSDGs）和流域共享社会经济路径（RiSSPs）。利用代理建模技术对黑河流域生态水文模型降维，生成上游生态水文代理模型和中下游生态水文代理模型，并通过地表需水和供水、土地利用变化、温度、降水等界面参数将上游生态水文代理模型、中下游生态水文代理模型、经济系统模型（CGE）、土地利用模型、人口增长模型、城市化模型、指标计算模型和可持续性评价模型集成，形成了黑河流域生态水文-社会经济集成模型。以此为基础，开发建立了黑河流域可持续发展决策支持系统[17]（图 6），该系统为 SDGs 在流域尺度和区域尺度上的实施和监测提供了新途径。

5 结语

黑河遥感站围绕流域科学中的地面与遥感综合观测、模型集成与可持续发展等科学问题，建立了流域

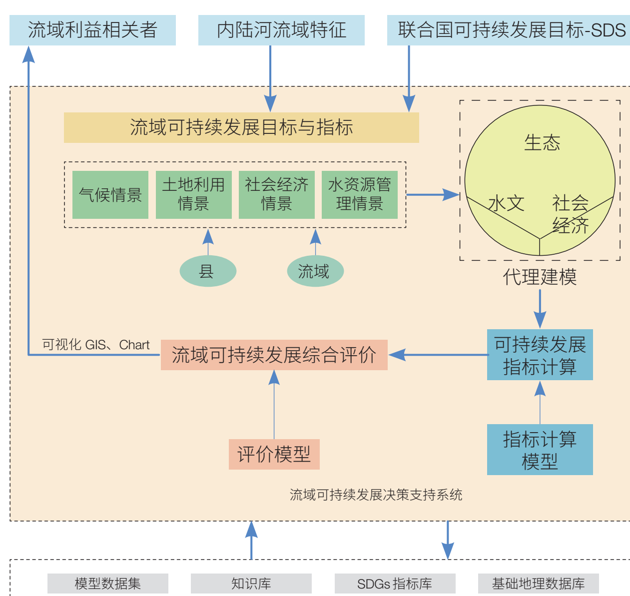

图 6 黑河流域可持续发展决策支持系统的核心设计思路

分布式、多尺度生态水文观测网络及遥感像元尺度地面真实性检验场，研发了一系列定量遥感产品，建立了流域集成模型，支持了遥感产品的真实性检验和自然与人文复杂过程的流域综合集成研究。黑河遥感站的观测和研究将在我国山水林田湖草等综合自然资源监测、祁连山国家公园建设，以及流域可持续发展战略中继续发挥先锋示范与科技支撑的重要作用。

参考文献

1 程国栋. 黑河流域模型集成. 北京: 科学出版社, 2019.

2 Cheng G D, Li X, Zhao W, et al. Integrated study of the water-ecosystem-economy in the Heihe River Basin. National Science Review, 2014, 1(3): 413-428.

3 唐霞, 张志强, 王勤花, 等. 黑河流域历史时期水资源开发利用研究. 干旱区资源与环境, 2015, 29(7): 89-94.

4 龚家栋, 程国栋, 张小由, 等. 黑河下游额济纳地区的环境演变. 地球科学进展, 2002, 17(4): 491-496.

5 李新, 程国栋, 马明国, 等. 数字黑河的思考与实践4：流域观测系统. 地球科学进展, 2010, 25(8): 866-876.

6 Li X, Liu S M, Xiao Q, et al. A multiscale dataset for understanding complex eco-hydrological processes in a heterogeneous oasis system. Scientific Data, 2017, 4: 170083

7 Liu S M, Li X, Xu Z W, et al. The Heihe integrated observatory network: A basin-scale land surface processes observatory in China. Vadose Zone Journal, 2018, 17(1): 1-21.

8 Che T, Li X, Liu S M, et al. Integrated hydrometeorological, snow and frozen-ground observations in the alpine region of the Heihe River Basin, China. Earth System Science Data, 2019, 11(3): 1483-1499.

9 Che T, Li X, Jin R, et al. Snow depth derived from passive microwave remote-sensing data in China. Annals of Glaciology, 2008, 49: 145-154.

10 Dai L Y, Che T, Ding Y J. Inter-calibrating SMMR, SSM/I and SSMI/S data to improve the consistency of snow-depth products in China. Remote Sensing, 2015, 7(6): 7212-7230.

11 Jin R, Zhang T J, Li X, et al., Mapping surface soil freeze-thaw cycles in China based on SMMR and SSM/I brightness temperatures from 1978 to 2008. Arctic, Antarctic, and Alpine Research, 2015, 47(2): 213-229.

12 Hao X H, Luo S Q, Che T, et al. Accuracy assessment of four cloud-free snow cover products over the Qinghai-Tibetan Plateau. International Journal of Digital Earth, 2019, 12(4): 375-393.

13 Jin R, Li X, Yan B P, et al. A nested ecohydrological wireless sensor network for capturing the surface heterogeneity in the midstream areas of the Heihe River Basin, China. IEEE Geoscience and Remote Sensing Letters, 2014, 11(11): 2015-2019.

14 Li H Y, Li X, Yang D W, et al. Tracing snowmelt paths in an integrated hydrological model for understanding seasonal snowmelt contribution at basin scale. Journal of Geophysical Research: Atmospheres, 2019, 124(16): 8874-8895.

15 Zhang Y L, Cheng G D, Li X, et al., Coupling of a simultaneous heat and water model with a distributed hydrological model and evaluation of the combined model in a cold region watershed. Hydrological Processes, 2013, 27(25): 3762-3776.

16 Li X, Cheng G D, Ge Y C, et al. Hydrological cycle in the Heihe River Basin and its implication for water resource management in endorheic basins. Journal of Geophysical Research: Atmospheres, 2018, 123(2): 890-914.

17 Ge Y C, Li X, Cai X M, et al. Converting UN sustainable development goals (SDGs) to decision-making objectives and implementation options at the river basin scale. Sustainability, 2018, 10(4): 1056.

Integration of Remote Sensing Observations and Models Supports the Regional Sustainable Development in Heihe River Basin, China

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Abstract The Heihe River Basin is the second largest inland river basin in China. During the last few decades, this region has been faced with a serious of severe ecological and environmental problems caused by rapid economic growth and climate change. Two decades ago, with the increase of population and water consumption in the upper and middle reaches, the ecological water consumption in the lower reaches was greatly squeezed, which eventually led to serious ecological disasters, such as the shrinkage of the natural oasis, the drying up of the lakes, and frequent sandstorms in the lower reaches. The sustainable development of the region has been seriously challenged. To accurately monitor changes in hydrological and meteorological variables at watershed scale and support the wise use of water resources in this region, the Heihe Remote Sensing Experimental Research Station (HRSERS) was founded in 2009. The foundation of HRSERS has greatly improved the level of scientific research and decision support in the Heihe River Basin. The main achievements include: (1) the first watershed scale (with an area of 143000 km^2) integrated observation system in China is constructed, and a large number of long-term observation data are obtained. More than 200 papers have been published using the observed dataset; (2) key eco-environmental variables in Heihe River Basin are retrieved from remote sensing data; (3) the theoretical framework and method system for the authenticity inspection of heterogeneous surface remote sensing products have been established, and some related national standards have been approved; (4) the eco-hydrological model is improved by adding glacier, snow and permafrost modular, and the eco-hydrology-economic coupling model is developed for the whole Heihe River Basin to full couple the natural processes and social processes; (5) the United Nations Sustainable Development Goals (SDGs) were monitored at the basin scale and regional scale, and provides scientific support for the sustainable development and decision-making of Heihe River Basin.

Keywords Heihe River Basin, remote sensing, integrated observation, validation, model integration, eco-hydrology, decision support, sustainable development

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参考文献（双语版）

1 程国栋. 黑河流域模型集成. 北京: 科学出版社, 2019.
Cheng G D. Model Integration of the Heihe River Basin. Beijing: Science Press, 2019. (in Chinese)

2 Cheng G D, Li X, Zhao W Z, et al. Integrated study of the water-ecosystem-economy in the Heihe River Basin. National Science Review, 2014, 1(3): 413-428.

3 唐霞, 张志强, 王勤花, 等. 黑河流域历史时期水资源开发利用研究. 干旱区资源与环境, 2015, 29(7): 89-94.
Tang X, Zhang Z Q, Wang Q H, et al. The history of water resources utilization of Heihe River Basin. Journal of Arid Land Resources and Environment, 2015, 29(7): 89-94. (in Chinese)

4 龚家栋, 程国栋, 张小由, 等. 黑河下游额济纳地区的环境演变. 地球科学进展, 2002, 17(4): 491-496.
Gong J D, Cheng G D, Zhang X Y, et al. Environmental changes of Ejina region in the lower reaches of Heihe River. Advance in Earth Sciences, 2002, 17(4): 491-496. (in Chinese)

5 李新, 程国栋, 马明国, 等. 数字黑河的思考与实践4：流域观测系统. 地球科学进展, 2010, 25(8): 866-876.
Li X, Cheng G D, Ma M G, et al. Digital Heihe River Basin 4: Watershed observing system. Advances in Earth Science, 2010, 25(8): 866-876. (in Chinese)

6 Li X, Liu S M, Xiao Q, et al. A multiscale dataset for understanding complex eco-hydrological processes in a heterogeneous oasis system. Scientific Data, 2017, 4: 170083

7 Liu S M, Li X, Xu Z W, et al. The Heihe integrated observatory network: A basin-scale land surface processes observatory in China. Vadose Zone Journal, 2018, 17(1): 1-21.

8 Che T, Shao Min L, Li H Y, et al. Integrated hydrometeorological, snow and frozen-ground observations in the alpine region of the Heihe River Basin, China. Earth System Science Data, 2019, 11(3): 1483-1499.

9 Che T, Li X, Jin R, et al. Snow depth derived from passive microwave remote-sensing data in China. Annals of Glaciology, 2008, 49: 145-154.

10 Dai L Y, Che T, Ding Y J. Inter-calibrating SMMR, SSM/I and SSMI/S data to improve the consistency of snow-depth products in China. Remote Sensing, 2015, 7(6): 7212-7230.

11 Jin R, Zhang T J, Li X, et al. Mapping surface soil freeze-thaw cycles in China based on SMMR and SSM/I brightness temperatures from 1978 to 2008. Arctic, Antarctic, and Alpine Research, 2015, 47(2): 213-229.

12 Hao X H, Luo S Q, Che T, et al. Accuracy assessment of four cloud-free snow cover products over the Qinghai-Tibetan Plateau. International Journal of Digital Earth, 2019, 12(4): 375-393.

13 Jin R, Li X, Yan B P, et al. A nested ecohydrological wireless sensor network for capturing the surface heterogeneity in the midstream areas of the Heihe River Basin, China. IEEE Geoscience and Remote Sensing Letters, 2014, 11(11): 2015-2019.

14 Li H Y, Li X, Yang D W, et al. Tracing snowmelt paths in an integrated hydrological model for understanding seasonal snowmelt contribution at basin scale. Journal of Geophysical Research: Atmospheres, 2019, 124(16): 8874-8895.

15 Zhang Y L, Cheng G D, Li X, et al. Coupling of a simultaneous heat and water model with a distributed hydrological model and evaluation of the combined model in a cold region watershed. Hydrological Processes, 2013, 27(25): 3762-3776.

16 Li X, Cheng G D, Ge Y C, et al. Hydrological cycle in the Heihe River Basin and its implication for water resource management in endorheic basins. Journal of Geophysical Research: Atmospheres, 2018, 123(2): 890-914.

17 Ge Y C, Li X, Cai X M, et al. Converting UN sustainable development goals (SDGs) to decision-making objectives and implementation options at the river basin scale. Sustainability, 2018, 10(4): 1056.