Review

Integrating Wastewater and Emergency Department Surveillance for Early Warning of Seasonal Influenza in the United States: Time-Lag Relationships and Predictive Modeling Approaches

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Abstract

Seasonal influenza continues to impose a substantial burden on healthcare systems in the United States, highlighting the need for timely surveillance approaches that can identify changes in viral circulation and anticipate increases in healthcare demand. Conventional clinical surveillance, although essential, may be influenced by healthcare-seeking behavior, diagnostic testing, and reporting practices. Wastewater-based surveillance has emerged as a complementary approach for monitoring community-level viral activity independently of individual healthcare encounters. This review examines the potential integration of wastewater surveillance and emergency department (ED) data for early detection of influenza activity in the United States, with particular emphasis on temporal associations, time-lag analysis, and predictive modeling. Wastewater measurements provide information on the circulation of influenza viral RNA within defined catchment populations, whereas ED surveillance captures clinical presentations and healthcare utilization associated with respiratory illness. Combining these complementary indicators may improve the characterization of influenza trends and provide additional information for public health and healthcare planning. Cross-correlation analysis and distributed lag models offer statistical approaches for investigating whether changes in wastewater viral signals precede corresponding changes in ED visits. Furthermore, time-series regression and machine learning methods, including random forests and gradient boosting, may help evaluate the predictive contribution of individual and integrated surveillance datasets. Comparisons between wastewater-only, ED-only, and integrated models, supported by appropriate performance measures and temporal validation, are essential for determining their relative predictive value. However, differences in geographic coverage, sampling frequency, laboratory procedures, and healthcare-seeking patterns may affect data integration and model generalizability. Overall, combining wastewater and ED surveillance represents a promising complementary strategy for influenza monitoring. Further prospective validation, standardized data collection, and cross-regional collaboration are needed to establish reliable early warning systems and support healthcare preparedness, resource allocation, and timely patient care.

Keywords: Influenza surveillance, Wastewater-based epidemiology, Emergency department, Predictive modeling, Early warning systems

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Graphical Abstract: Integrating Wastewater and Emergency Department Surveillance for Early Warning of Seasonal Influenza in the United States. Wastewater surveillance and emergency department (ED) data provide complementary indicators of influenza activity, reflecting community-level viral circulation and healthcare utilization, respectively. Cross-correlation and distributed lag models can identify temporal associations, while time-series regression and machine learning approaches can evaluate predictive performance. Comparing wastewater-only, ED-only, and integrated models may help determine their relative predictive value. Combining these approaches may strengthen influenza early warning systems, improve healthcare preparedness, and support timely public health decisions and resource allocation.

Introduction

Seasonal influenza remains a major public health concern in the United States, contributing to substantial illness, healthcare utilization, and seasonal pressure on healthcare systems (1). Timely recognition of increasing influenza activity is important for public health planning and hospital preparedness (2). However, conventional surveillance systems have some limitations. Clinical reports often depend on healthcare-seeking behavior, diagnostic testing, and reporting practices (3). As a result, changes in reported influenza activity may not fully reflect the timing or extent of viral circulation in the community (3). Wastewater-based surveillance has emerged as a complementary approach for monitoring infectious diseases at the population level (4). By detecting viral genetic material in wastewater, this method can provide information about community-level viral circulation without requiring individuals to seek medical care or undergo diagnostic testing (4). Nevertheless, wastewater data alone cannot describe the number of people seeking medical attention or the resulting demand on healthcare services. Integrating wastewater-based surveillance with clinical surveillance may provide a more comprehensive understanding of influenza activity at the population level (5). Examining the temporal relationship between these data sources may also help identify potential early warning signals (5). This review discusses the integration of wastewater and emergency department surveillance in the United States, with particular attention to time-lag relationships, predictive modeling approaches, and their potential

applications in public health and healthcare planning.

Wastewater-Based Surveillance of Influenza in the United States

Wastewater-based surveillance offers an additional approach for monitoring influenza virus circulation at the community level (6). The method relies on detecting viral genetic material in wastewater collected from treatment plants or other sampling sites (6). Respiratory viruses, including influenza virus and respiratory syncytial virus (RSV), can be detected in wastewater and sewage sludge, reflecting the presence of viral genetic material in human waste (7). Laboratory methods, particularly reverse transcription quantitative polymerase chain reaction (RT-qPCR), can be used to detect and quantify influenza viral RNA in collected samples (8). In the United States, wastewater surveillance has increasingly been explored for monitoring influenza A and, where suitable assays are available, influenza B (9). Tracking these viral signals may provide information about changes in community-level influenza activity (9). Unlike clinical surveillance, wastewater monitoring does not depend directly on individuals seeking medical care or undergoing diagnostic testing (10). This feature may help capture viral circulation among people with mild or unrecognized infections. However, wastewater surveillance also has important limitations. Viral concentrations can be influenced by sampling conditions, wastewater flow, environmental factors, and differences in laboratory methods (11). In addition, the detection of viral RNA does not necessarily indicate the presence of infectious viral particles, nor does the measured RNA concentration directly correspond to the exact number of infected individuals (11). Geographic coverage and sampling frequency may also vary across states and communities (12). Therefore, wastewater findings are best interpreted alongside complementary epidemiological and clinical data.

Emergency Department Surveillance as a Clinical Indicator of Influenza Activity

Emergency department (ED) visits provide an important clinical indicator of influenza activity in the community (13). During periods of increased influenza circulation, the number of patients presenting with influenza-like illness or laboratory-confirmed influenza may rise (13). Monitoring these visits can help describe changes in healthcare demand and identify periods of increased pressure on emergency services (14). In the United States, clinical and syndromic surveillance systems collect information from healthcare facilities and support the monitoring of respiratory illness trends (15). When reported regularly, these data can provide relatively timely insights into patterns of patient presentations and changes in healthcare utilization (15). Unlike wastewater surveillance, ED data capture healthcare encounters among individuals seeking medical attention and therefore provide a direct measure of healthcare utilization associated with respiratory illness (16). However, ED surveillance has several limitations. Not all individuals with influenza seek emergency care, and healthcare-seeking behavior may differ across age groups, regions, and seasons (17). In addition, influenza-like symptoms are not specific to influenza and may result from other respiratory infections (17). Variations in diagnostic testing, case definitions, and reporting practices can also affect the interpretation of surveillance data (18). These factors should be considered when using ED visits to assess influenza activity or develop predictive models.

Integrating Wastewater and Emergency Department Surveillance Data

Wastewater and ED surveillance provide different but complementary information about

influenza activity (19). Wastewater measurements reflect viral signals at the community level, whereas ED records capture patients who seek medical care for respiratory symptoms (19). Considering these sources together may provide a more complete picture of influenza activity than either source alone (20). In particular, Wastewater data may help characterize changes in community-level viral circulation, while clinical surveillance data provide complementary information on the occurrence of infections among individuals seeking medical care (21). Integrating these datasets requires attention to differences in sampling frequency, geographic coverage, and reporting methods (22). Wastewater measurements are generally linked to specific treatment plants and their catchment areas, whereas ED data may be reported at the facility, regional, or state level (21). Aligning these geographic units and observation periods is therefore an important step in data integration. Statistical approaches can then be used to examine temporal associations between wastewater viral concentrations and influenza-related clinical indicators, including hospitalization rates and outpatient visits for influenza-like illness (23). The combined use of these data sources may also support the development of more informative early warning systems. For example, changes in wastewater signals could be assessed alongside trends in ED visits to identify possible increases in influenza activity (16). Such integration may help public health authorities interpret emerging trends and support decisions about healthcare preparedness. However, its practical value depends on data quality, consistent reporting, and appropriate model validation.

Time-Lag Relationships Between Wastewater Signals and Emergency Department Visits

Understanding the temporal relationship between pathogen signals in wastewater and clinical disease indicators is important for evaluating the potential of integrated surveillance systems (24). Changes in wastewater viral concentrations may precede corresponding changes in clinical activity, sometimes by several days or weeks (24). Assessing the temporal patterns of these changes may help clarify how wastewater-based influenza signals relate to changes in clinical disease burden and support their potential use in monitoring influenza activity (25). Several statistical approaches can be used to examine these temporal patterns. Cross-correlation analysis assesses the strength and direction of associations between two time series at different time lags (26). It can help determine whether changes in wastewater signals are associated with ED visits during the same week or precede changes in ED visits at subsequent time intervals (26). However, it does not establish a causal relationship or, by itself, demonstrate reliable predictive value. PRESENS provide a complementary approach by estimating the association of wastewater measurements with clinical outcomes across multiple time intervals (27). Unlike cross-correlation analysis, distributed lag models can estimate the contributions of different lag periods within a single statistical framework (28). This approach allows the temporal distribution of associations between wastewater signals and clinical indicators to be examined more comprehensively (28). However, the timing and strength of these associations may vary across states. Differences in sampling frequency, population characteristics, healthcare-seeking behavior, and seasonal influenza patterns may contribute to this variability (29). Therefore, lag estimates should be interpreted within their geographical and epidemiological context. Examining these differences is essential for determining whether

temporal patterns are sufficiently consistent to support the development of early warning strategies.

Predictive Modeling for Early Detection of Influenza Activity

Predictive modeling provides a framework for evaluating how the integration of multiple surveillance data sources can improve the accuracy of influenza activity estimates (30). Different modeling approaches may be appropriate depending on the characteristics of the available data sources and the specific forecasting objectives (30). Time-series regression models, including autoregressive and regression-based approaches, can account for temporal dependencies, seasonal patterns, and associations between surveillance indicators (31). Machine learning methods, such as random forests and gradient boosting, offer alternative approaches for identifying potentially complex and nonlinear relationships among environmental and clinical variables (31). However, their performance depends on data quality, sample size, and appropriate model development. An important step is to compare models based on different surveillance inputs. Wastewater-only models use viral measurements to estimate influenza activity, whereas ED-only models rely on clinical surveillance indicators (32). Integrated models combine both sources to assess whether their joint contribution improves predictive performance (33). These comparisons should use consistent outcome definitions, prediction periods, and validation procedures to ensure meaningful evaluation (33). Model performance can be assessed using measures such as mean absolute error (MAE) and root mean square error (RMSE) for continuous outcomes (34). Sensitivity, specificity, and area under the receiver operating characteristic curve (AUC) may also be appropriate when predicting predefined levels of influenza activity (35, 36). Temporal validation using data from influenza seasons not included in model training is particularly important (34). Ultimately, well-validated models may help estimate changes in influenza activity and anticipate periods of increased ED demand, providing potentially useful information for healthcare planning (37).

Limitations and Future Perspectives

Despite its potential, integrating wastewater and emergency department surveillance faces several challenges. Geographic and demographic differences may influence both viral signals and patterns of healthcare utilization. In addition, variations in wastewater sampling frequency, laboratory procedures, and clinical reporting can limit comparisons across states. Differences in geographic coverage may also make it difficult to align environmental measurements with emergency department data. Future studies should address these challenges through improved data harmonization and more standardized surveillance methods. Prospective validation across different regions and influenza seasons is also needed to assess the reliability of integrated predictive models. Greater coordination between environmental monitoring programs and healthcare surveillance systems may further support the development of practical and consistent early warning frameworks.

Conclusion

Wastewater and emergency department surveillance provide complementary information on influenza activity at the community and clinical levels. Integrating these data sources may improve the understanding of temporal changes in viral circulation and healthcare utilization. Examining their time-lag relationships and predictive value is particularly important for developing more informative early warning approaches. With improved data integration, standardized methods, and further validation,

combined surveillance systems may support public health planning and seasonal influenza preparedness in the United States.

Implications for Patient Care

Integrating wastewater and emergency department (ED) surveillance may have practical implications for patient care by providing complementary information on changes in influenza activity. Monitoring trends in both data sources could help identify periods of increasing influenza activity and support earlier recognition of potential increases in healthcare demand. Such information may assist healthcare facilities in preparing for periods of increased patient volume through timely adjustments in staffing, bed capacity, diagnostic resources, and other ED services. At the population level, combining environmental and clinical surveillance data across multiple states may improve the understanding of regional differences in influenza activity and help identify areas requiring additional healthcare attention. These integrated approaches could support more informed clinical service planning and resource allocation, potentially improving healthcare system preparedness and the timely delivery of care during seasonal influenza outbreaks. Their effective implementation, however, depends on reliable data sharing, consistent reporting practices, and coordination between public health agencies and healthcare facilities.

Conflict of Interest

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Ethics Statement

The author confirms that all ethical principles of research and scientific publication, including plagiarism prevention, data integrity, and avoidance of duplicate publication, have been fully observed.

Data Availability Statement

No new data were generated or analyzed during this study. All information discussed in this review is available in the published literature cited in the manuscript.

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Author Contributions

HN was responsible for the conceptualization, literature search, data collection, interpretation of the literature, and preparation and critical revision of the manuscript. The author read and approved the final version of the manuscript.

Artificial Intelligence (AI) Disclosure

No artificial intelligence (AI) tools were used in the preparation, writing, or editing of this manuscript.

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